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(12) **United States Patent**
Zhu(10) **Patent No.:** **US 8,841,427 B2**
(45) **Date of Patent:** **Sep. 23, 2014**(54) **METHODS FOR INTRODUCING MANNOSE 6-PHOSPHATE AND OTHER OLIGOSACCHARIDES ONTO GLYCOPROTEINS AND APPLICATIONS THEREOF**(71) Applicant: **Yunxiang Zhu**, Wayland, MA (US)(72) Inventor: **Yunxiang Zhu**, Wayland, MA (US)(73) Assignee: **Genzyme Corporation**, Cambridge, MA (US)

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C12P 21/00 (2006.01)(52) **U.S. Cl.**CPC **C12N 9/2465** (2013.01); **A61K 31/7024** (2013.01); **C07H 11/04** (2013.01); **C07K 14/47** (2013.01); **A61K 38/1709** (2013.01); **C12P 21/005** (2013.01)
USPC **530/409**; 530/411; 514/20.9; 514/53; 514/61(58) **Field of Classification Search**None
See application file for complete search history.(56) **References Cited**

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Primary Examiner — Eric Olson(74) *Attorney, Agent, or Firm* — Finnegan, Henderson, Farabow, Garrett & Dunner, LLP(57) **ABSTRACT**

Methods to introduce highly phosphorylated mannopyranosyl oligosaccharide derivatives containing mannose-6-phosphate (M6P), or other oligosaccharides bearing other terminal hexoses, to carbonyl groups on oxidized glycans of glycoproteins while retaining their biological activity are described. The methods are useful for modifying glycoproteins, including those produced by recombinant protein expression systems, to increase uptake by cell surface receptor-mediated mechanisms, thus improving their therapeutic efficacy in a variety of applications.

5 Claims, 14 Drawing Sheets

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U.S. Appl. No. 11/264,255: Office Action dated Jun. 25, 2008.

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U.S. Appl. No. 12/523,631: Office Action dated Oct. 23, 2012.

U.S. Appl. No. 13/140,272: Office Action dated May 16, 2013.

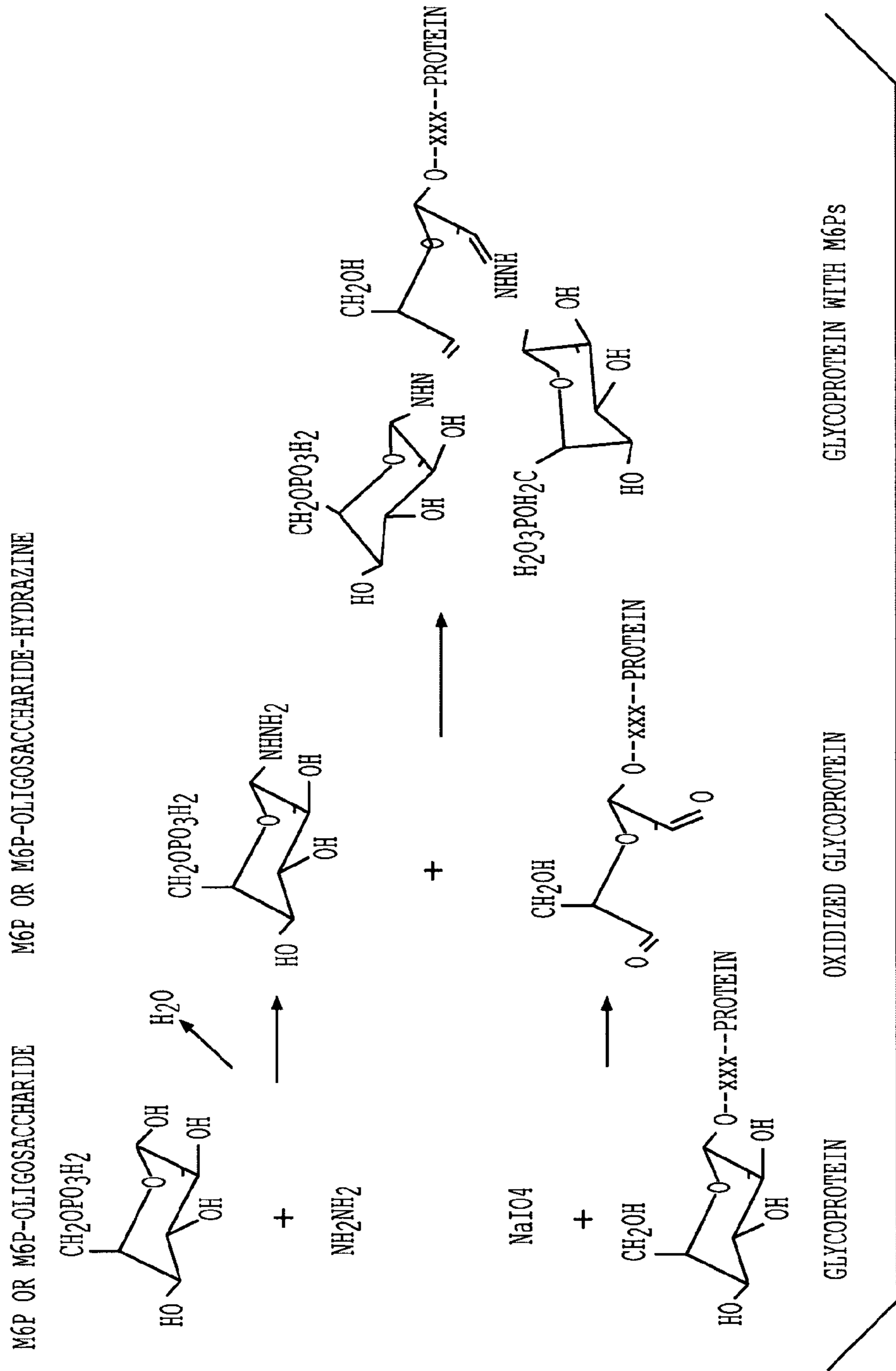
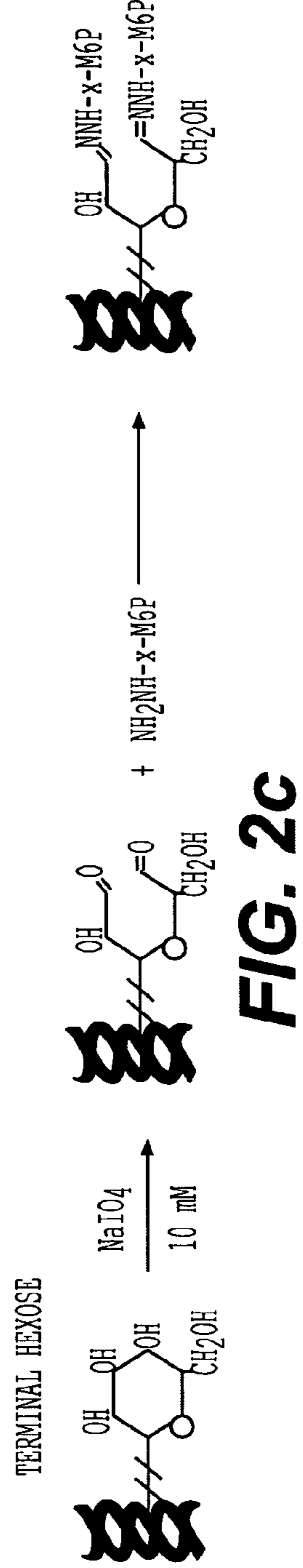
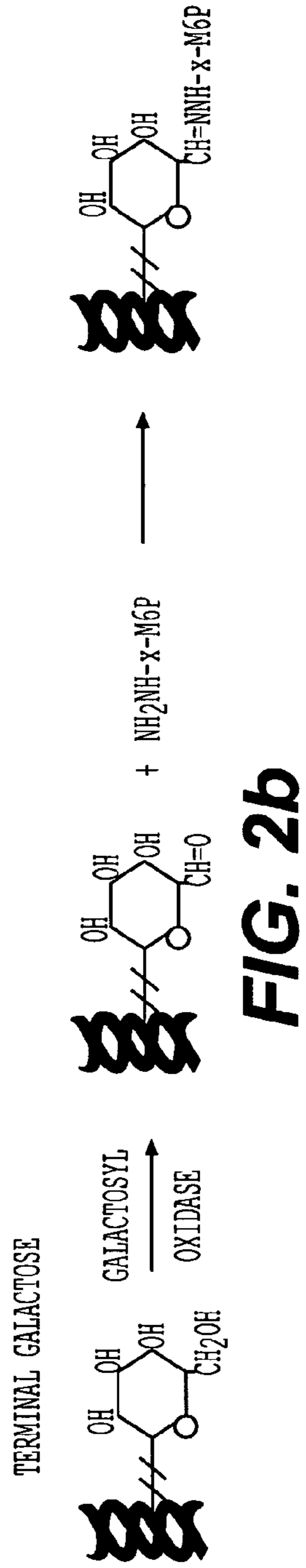
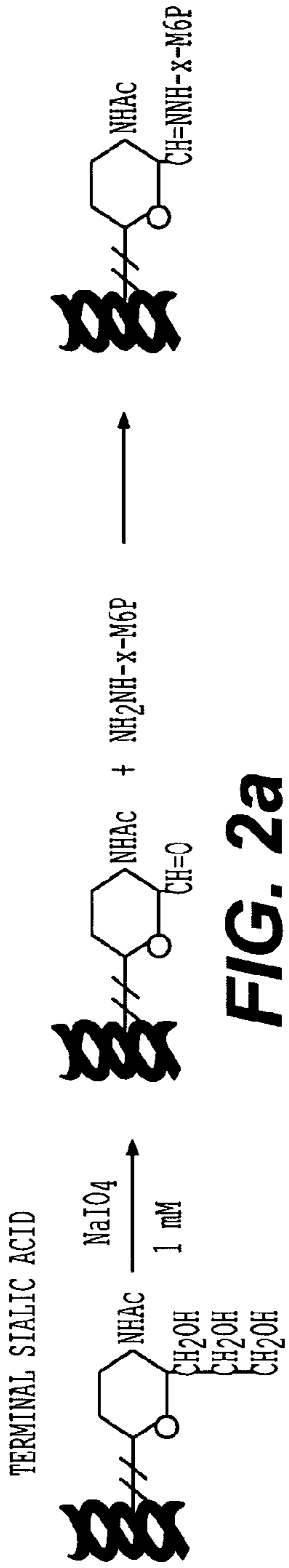


FIG. 1



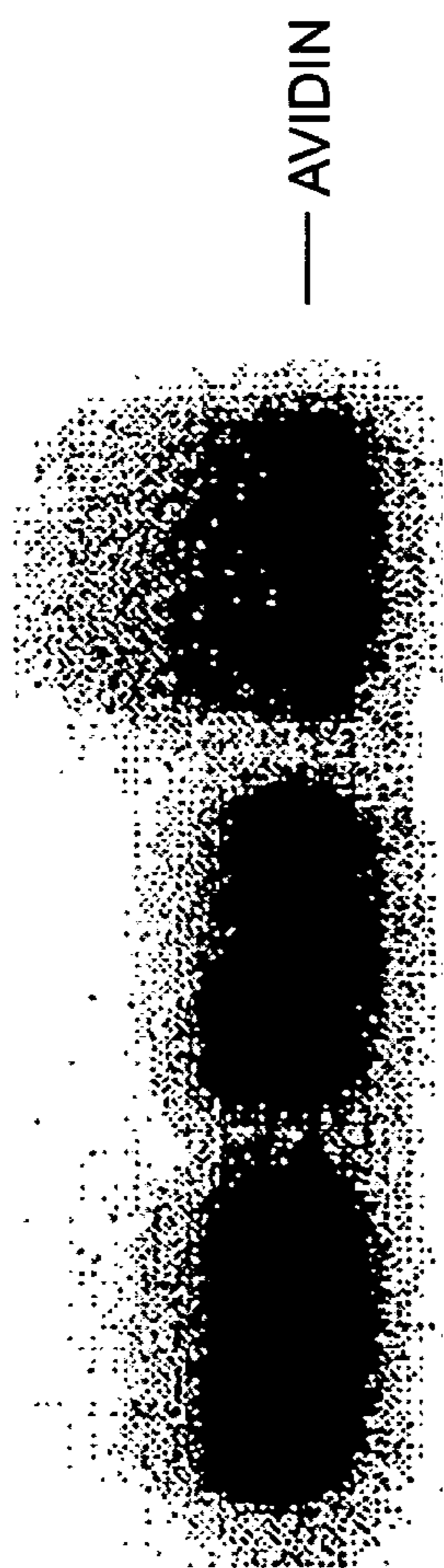


FIG. 3

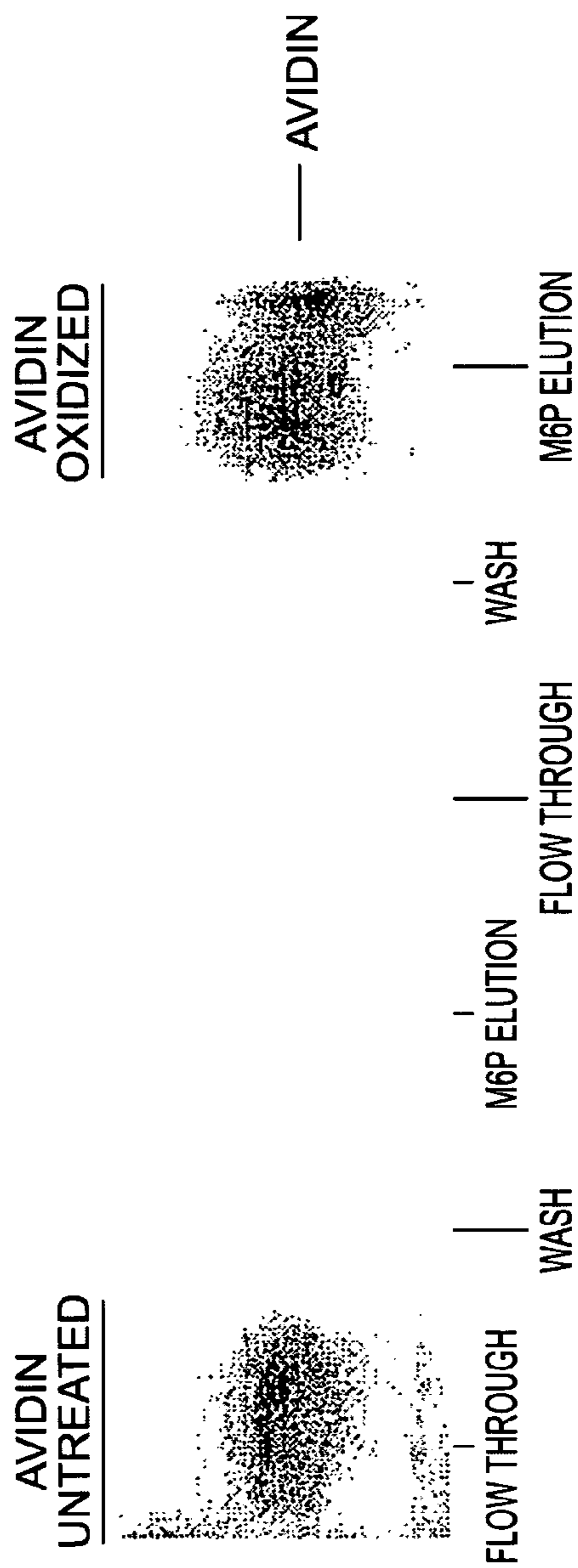


FIG. 4

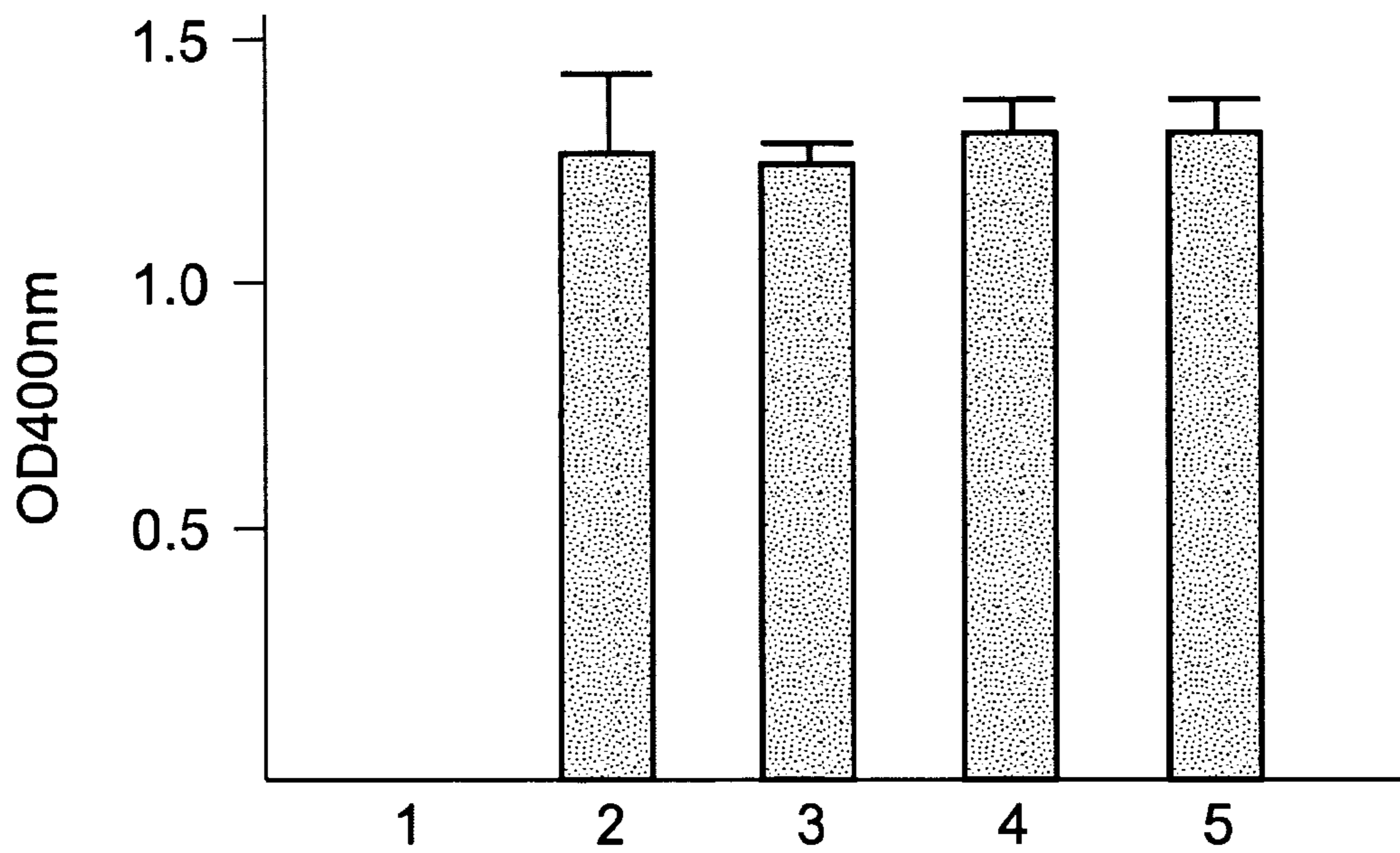


FIG. 5

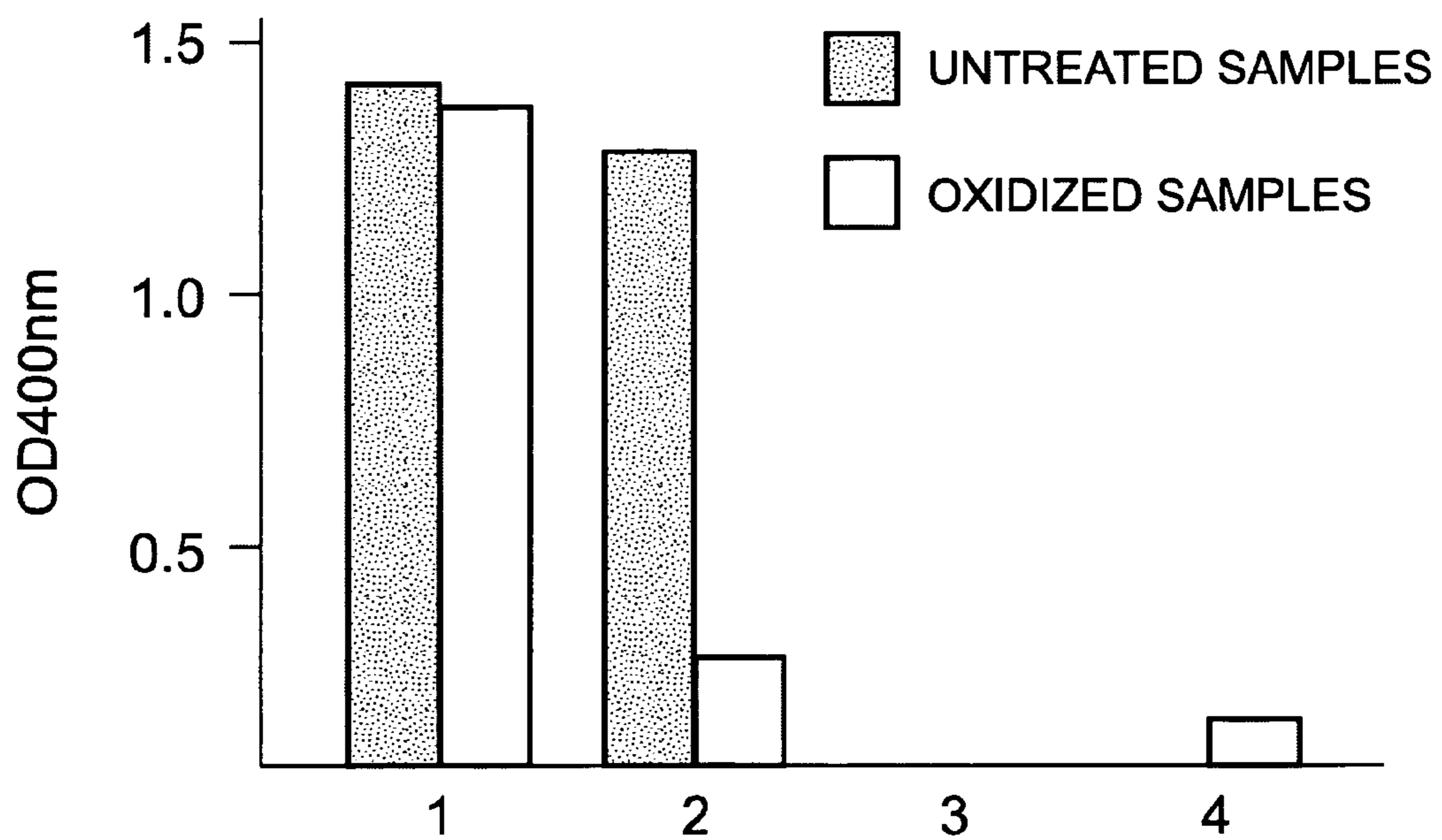


FIG. 6

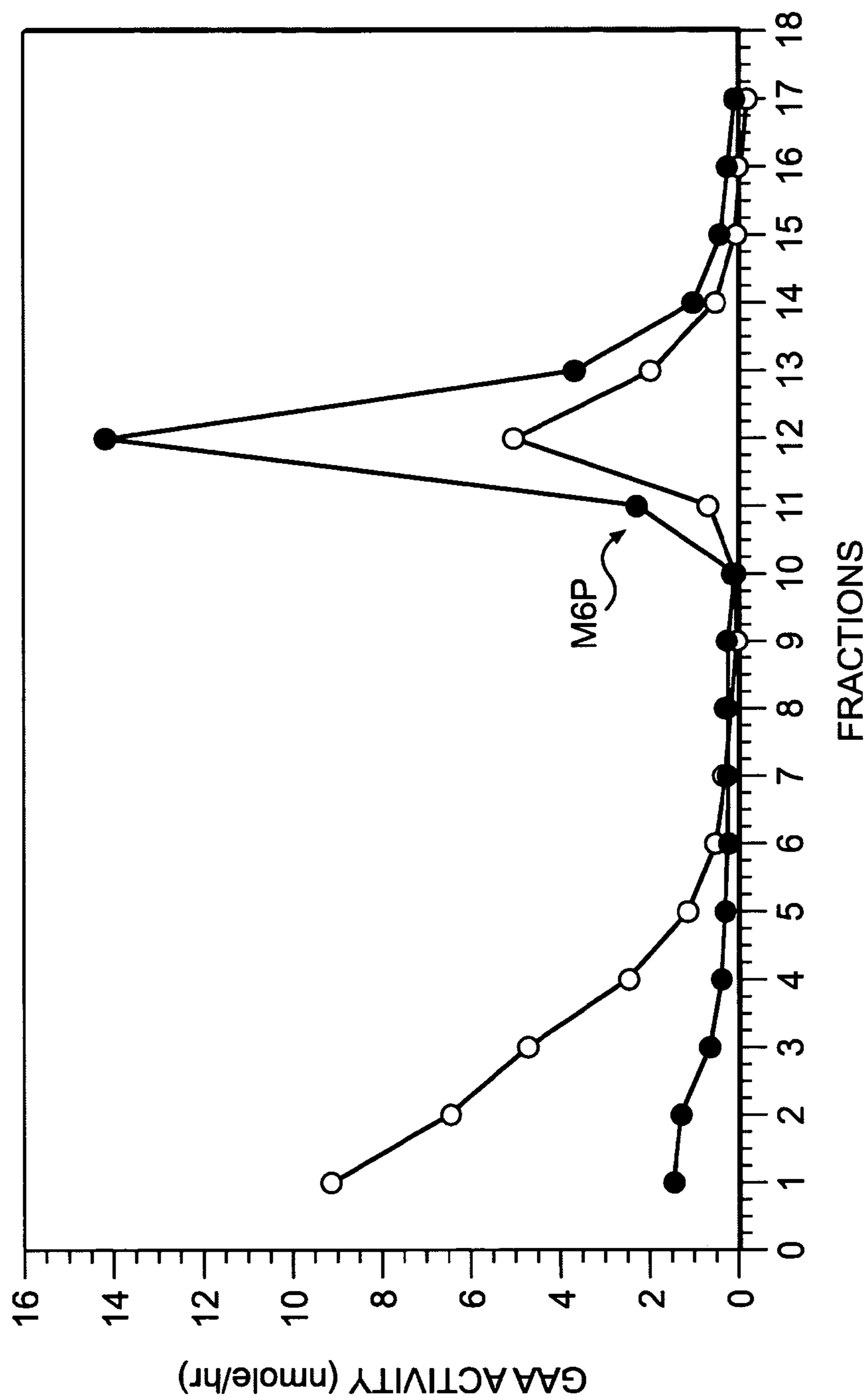


FIG. 7

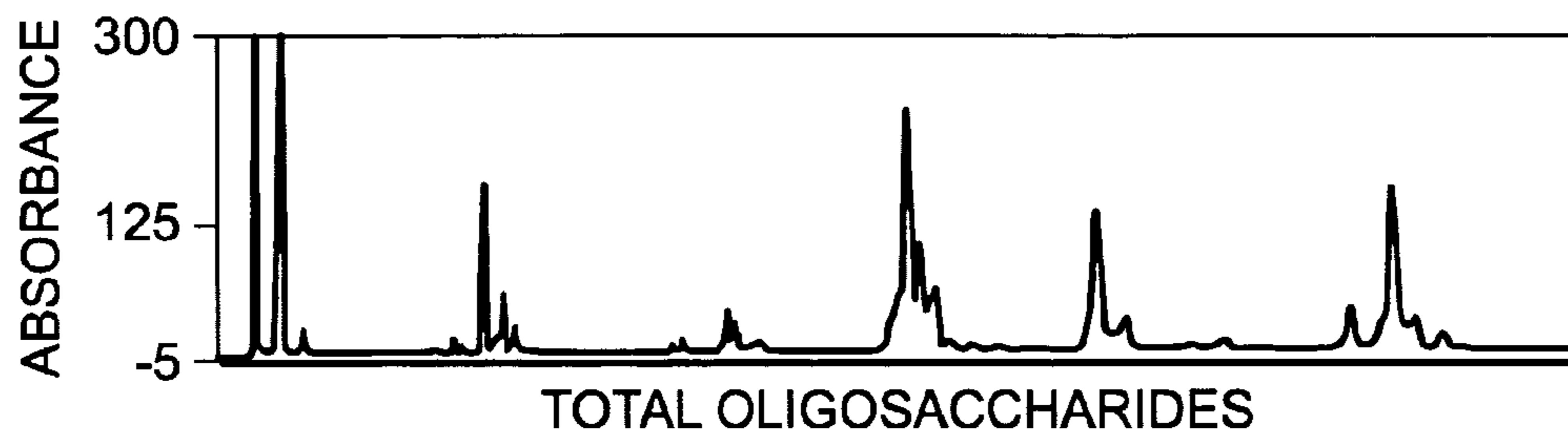


FIG. 8a

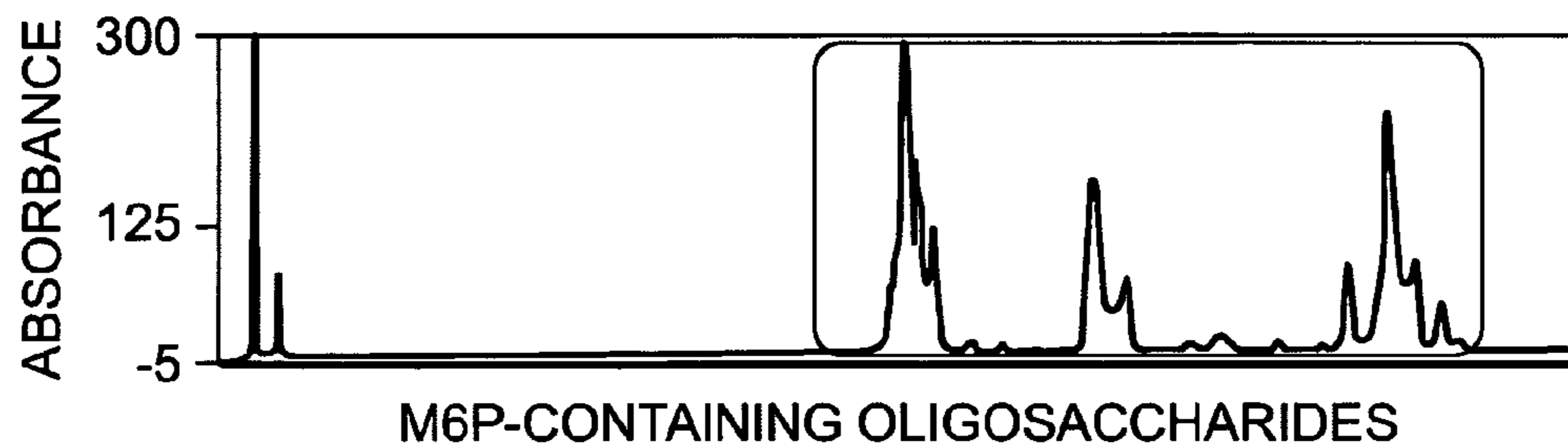


FIG. 8b

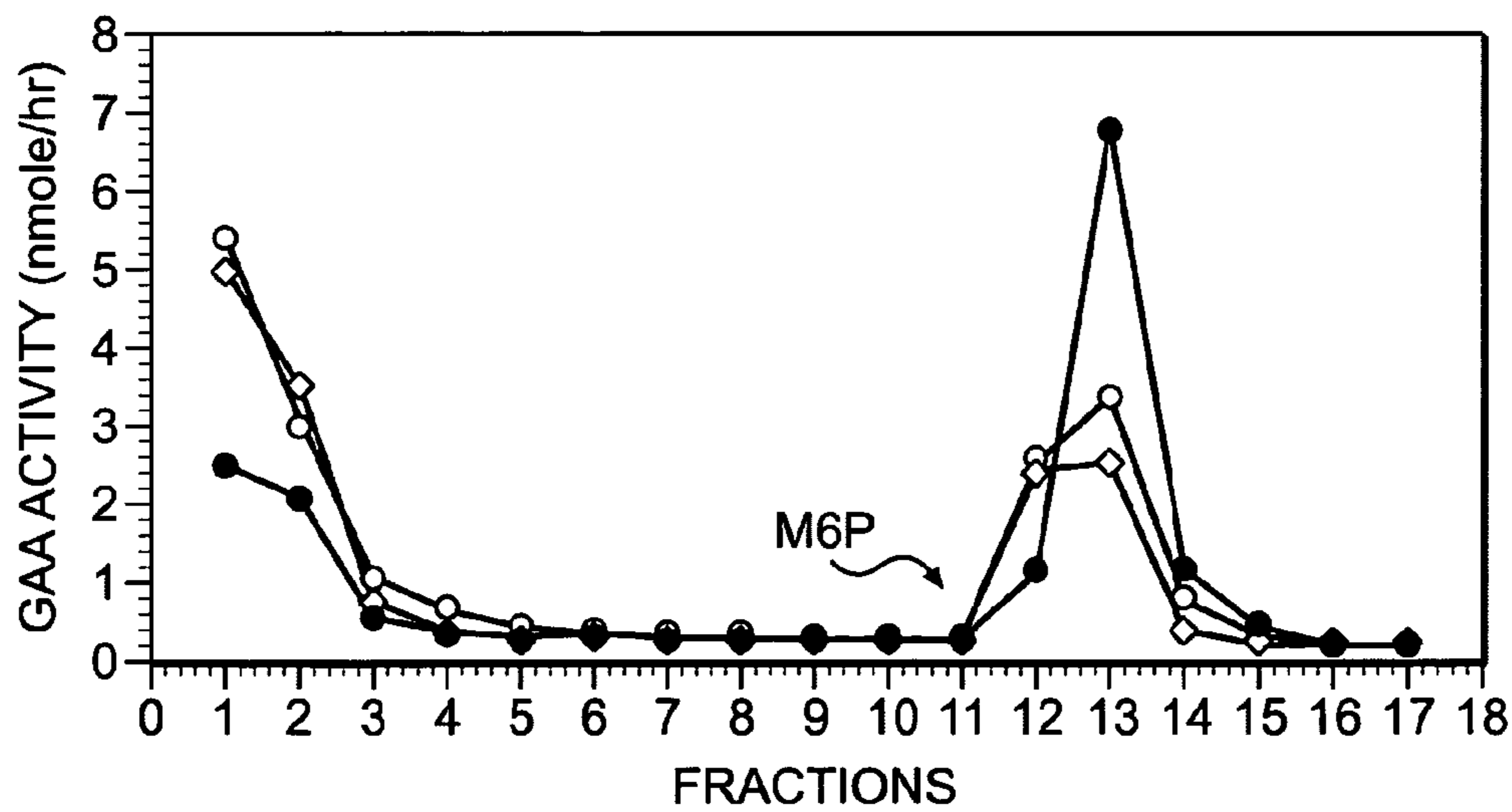


FIG. 9

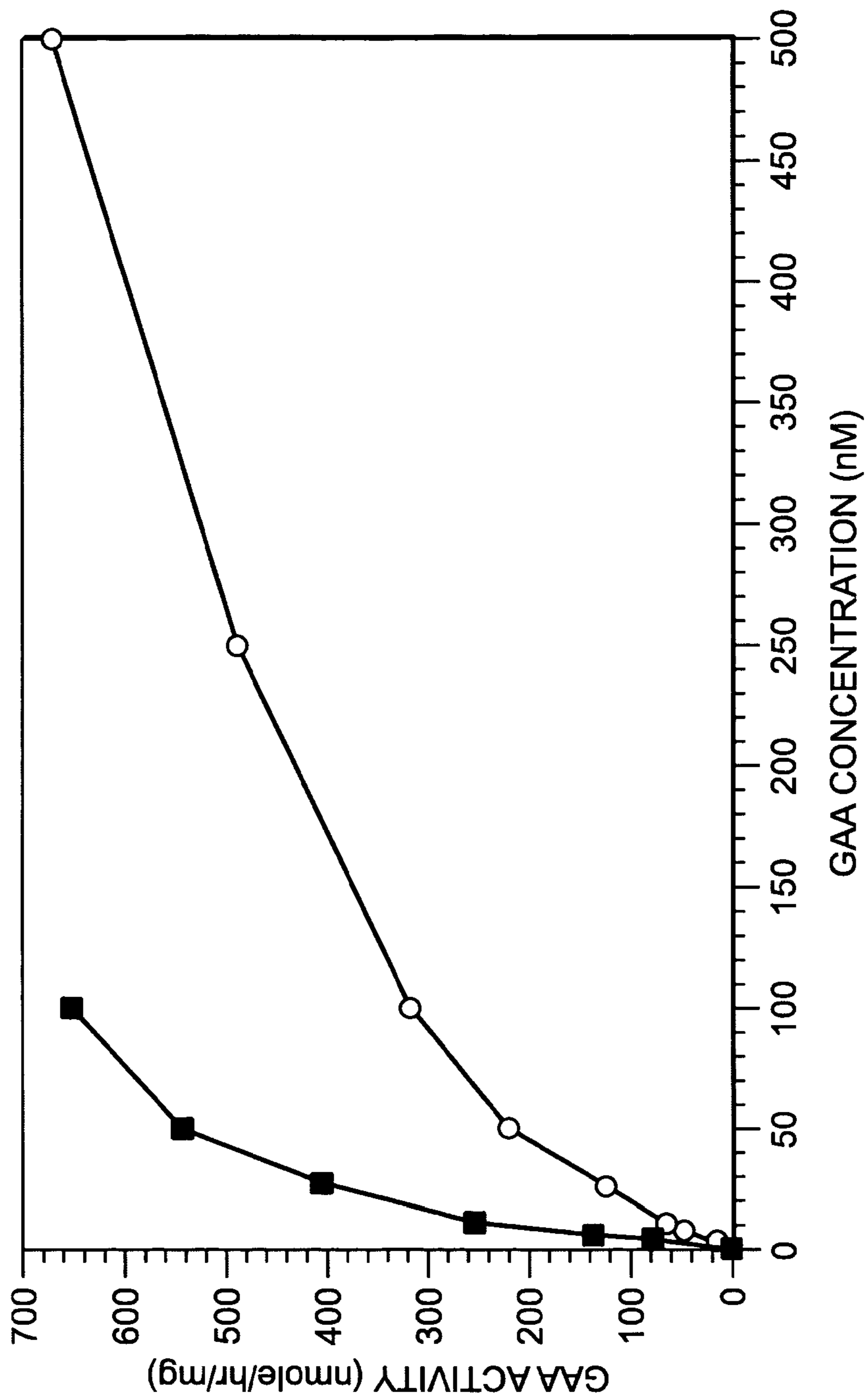


FIG. 10

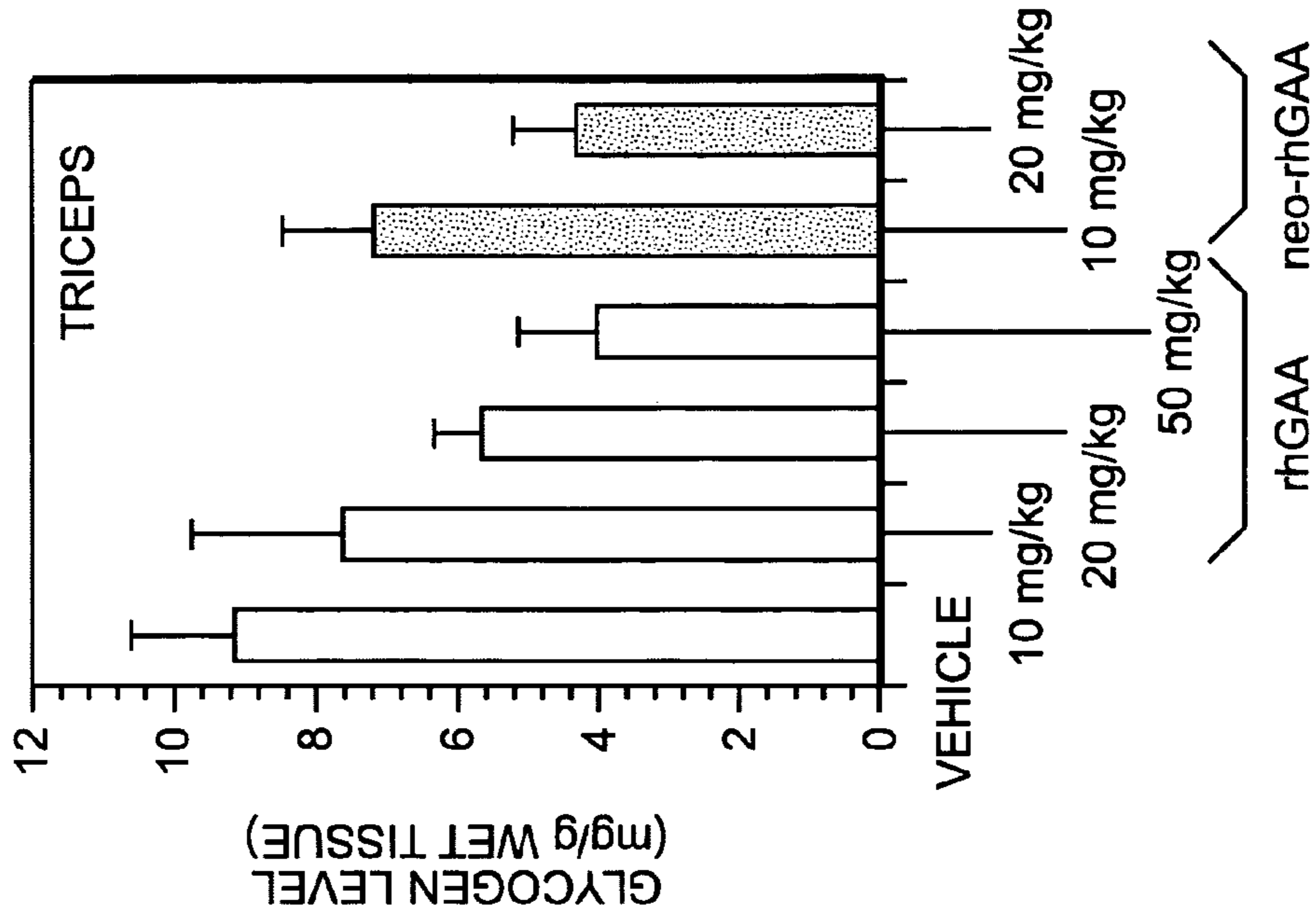


FIG. 11b

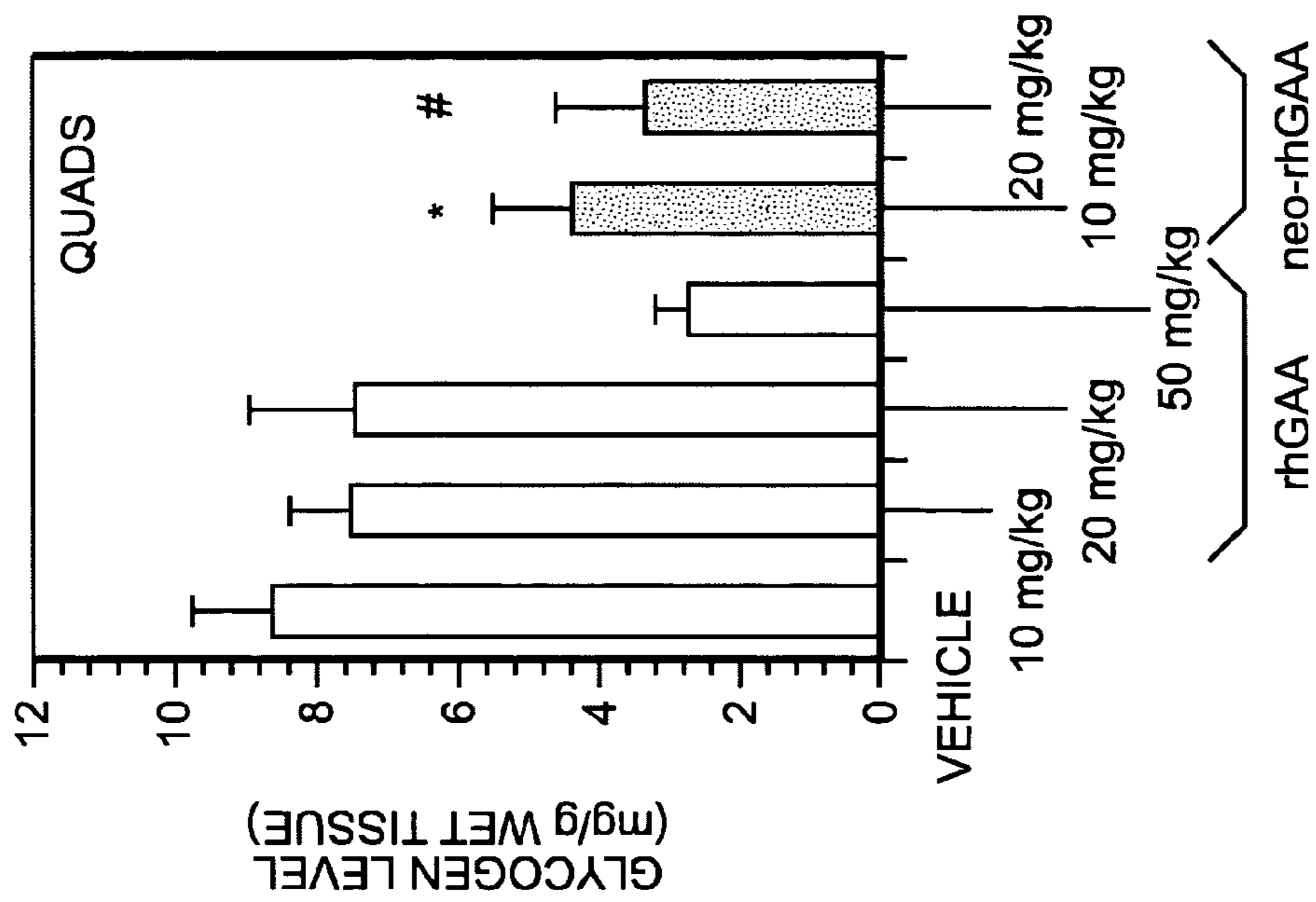


FIG. 11a

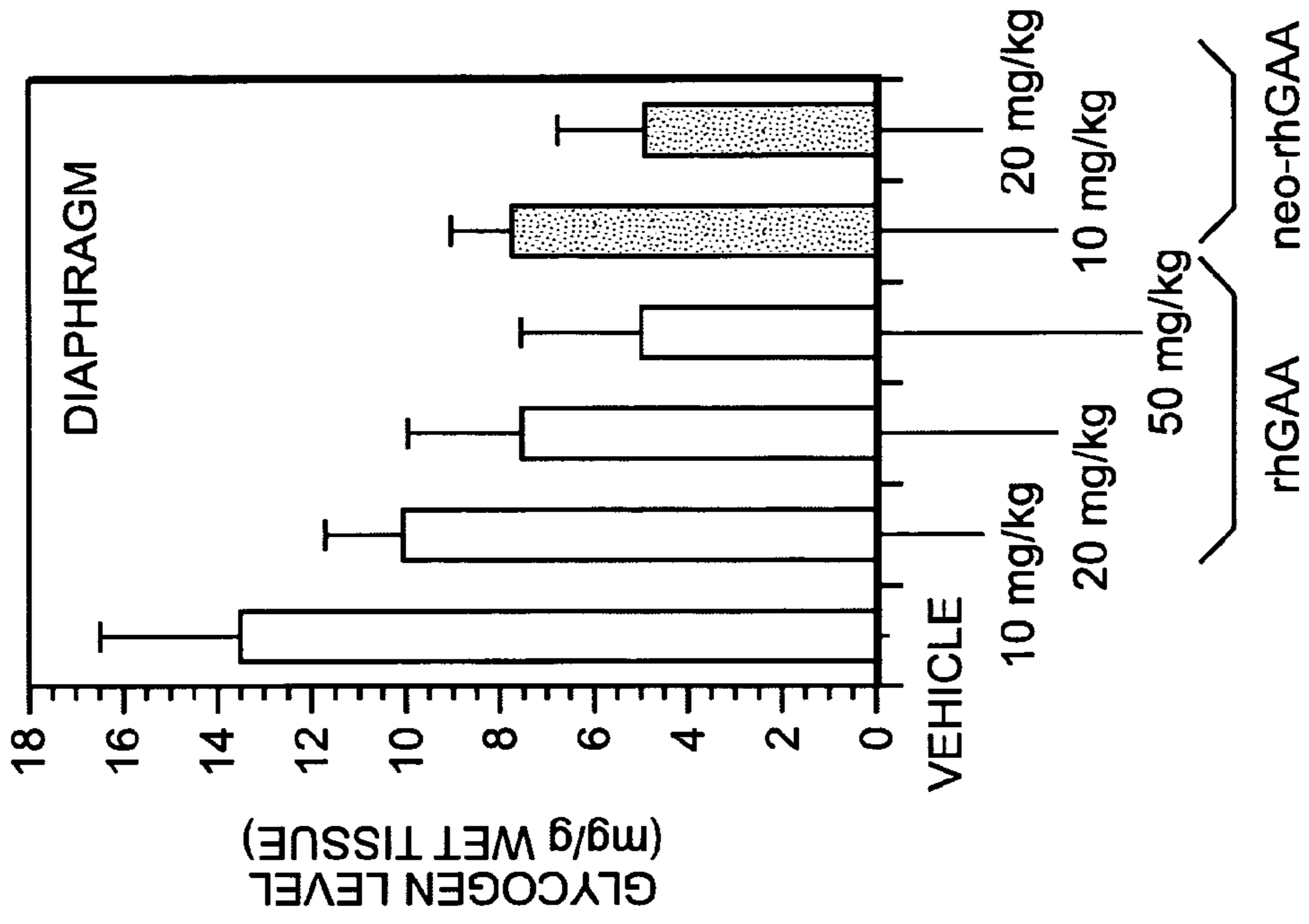


FIG. 11d

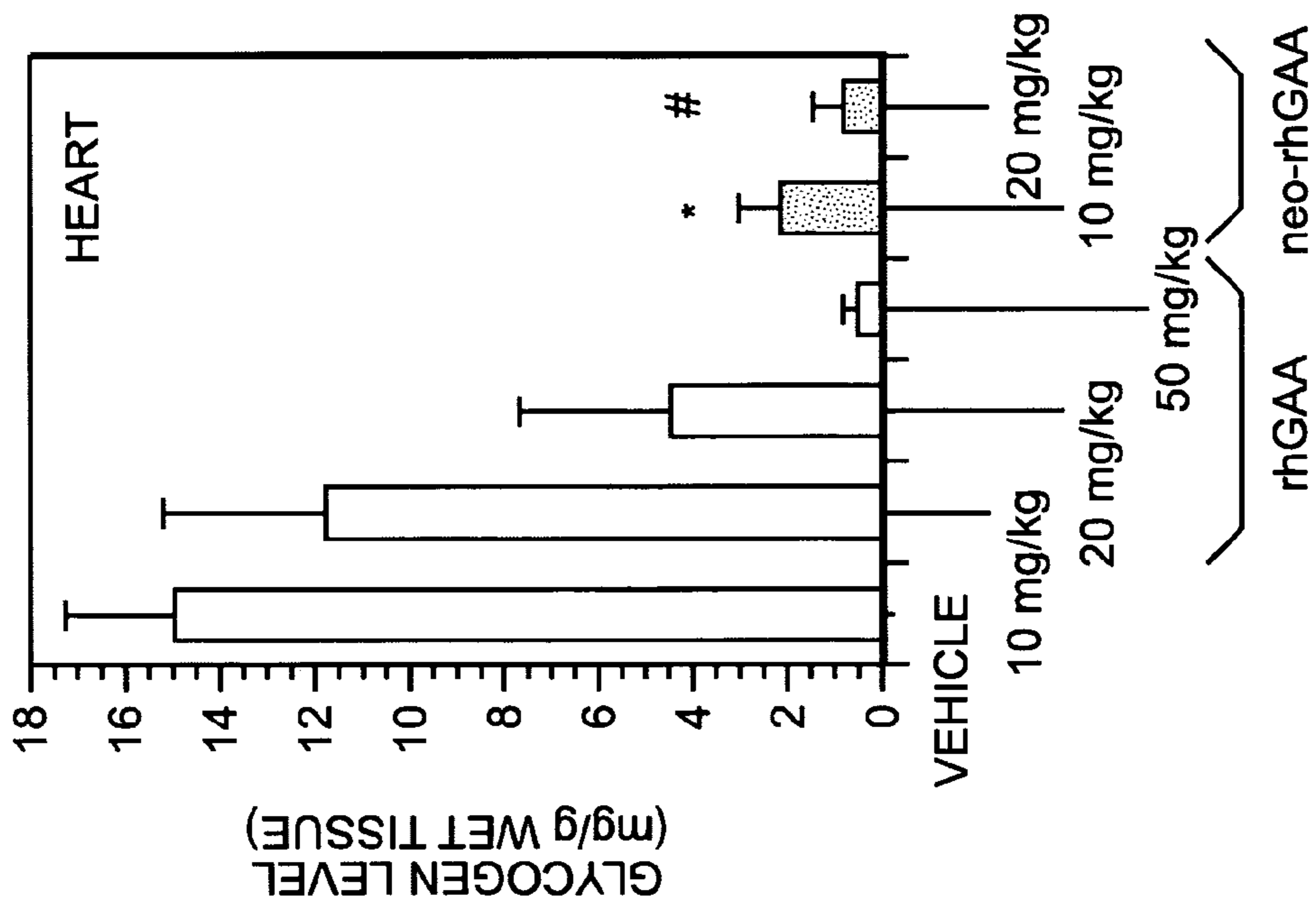


FIG. 11c

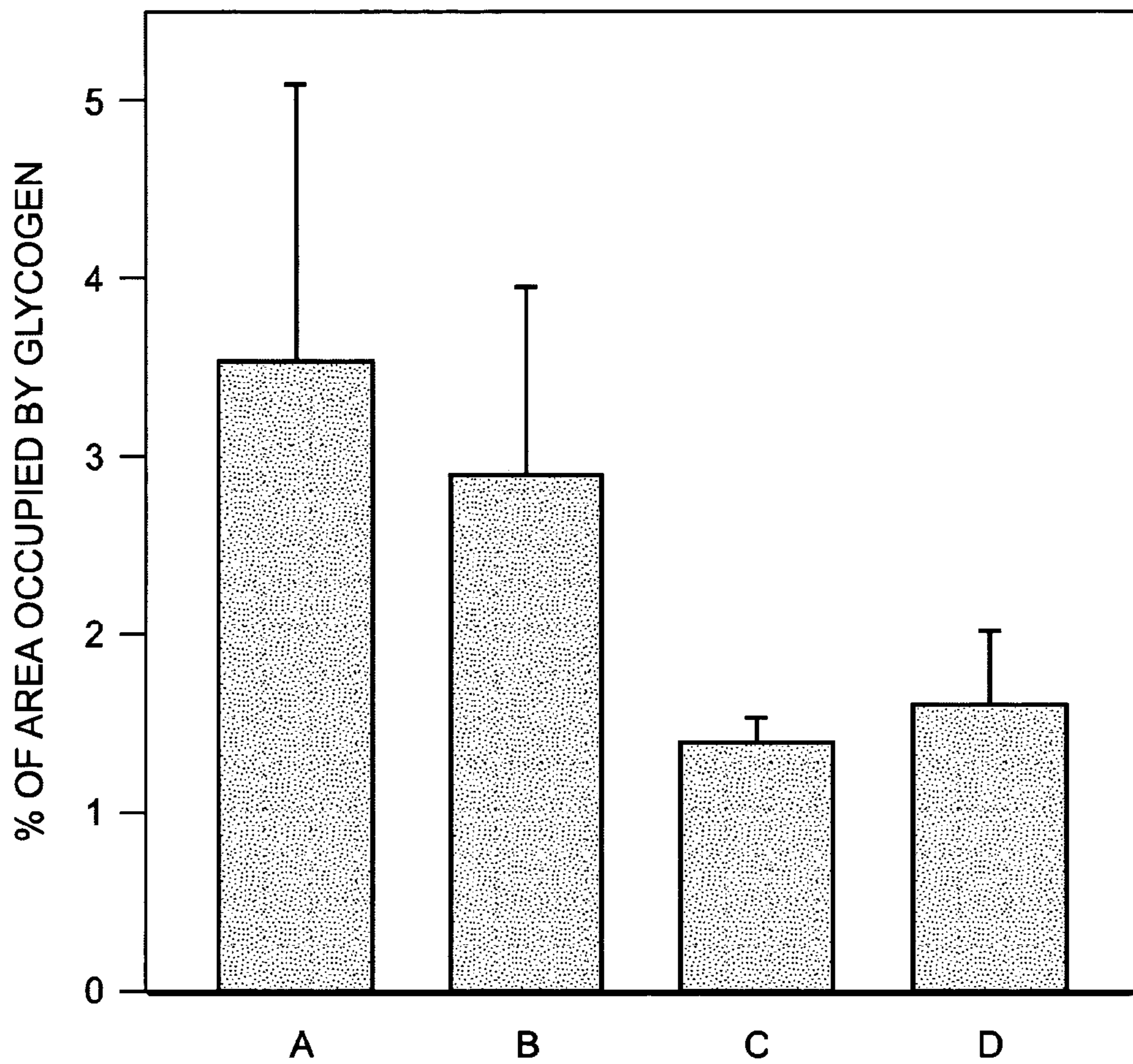


FIG. 12

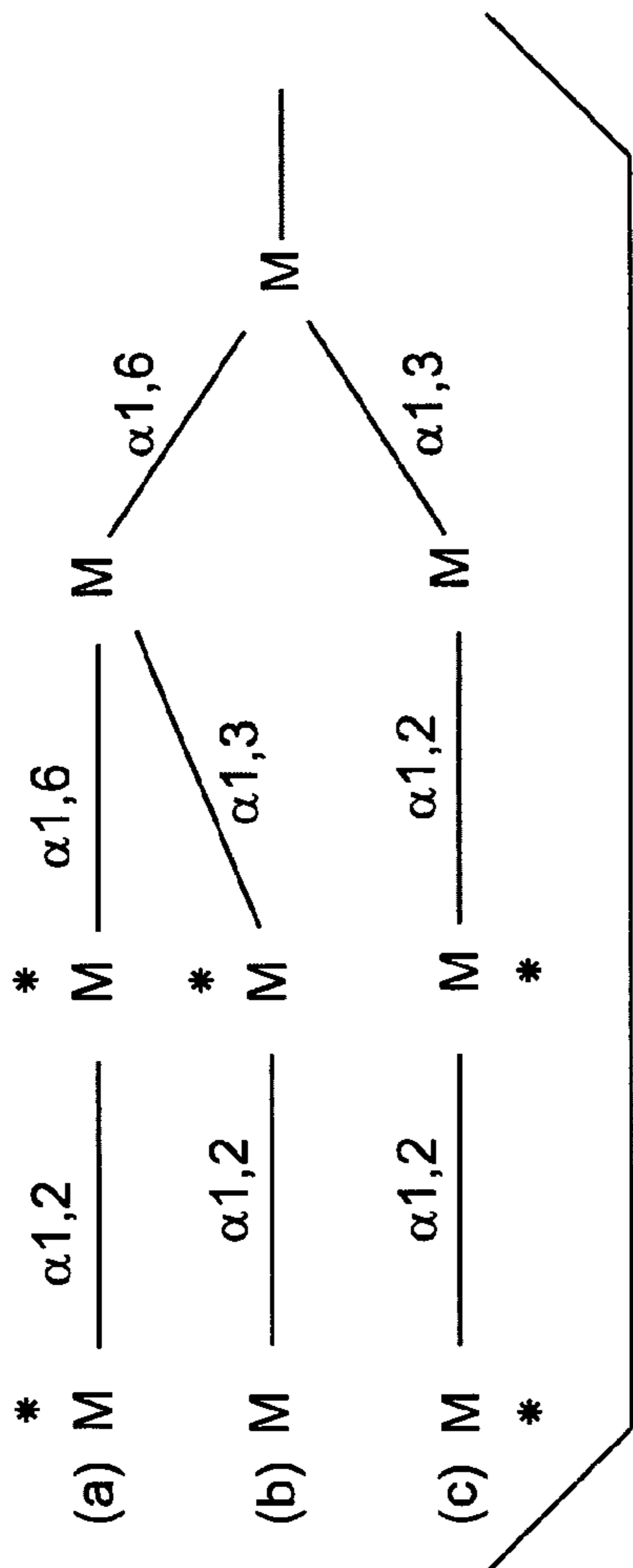


FIG. 13a

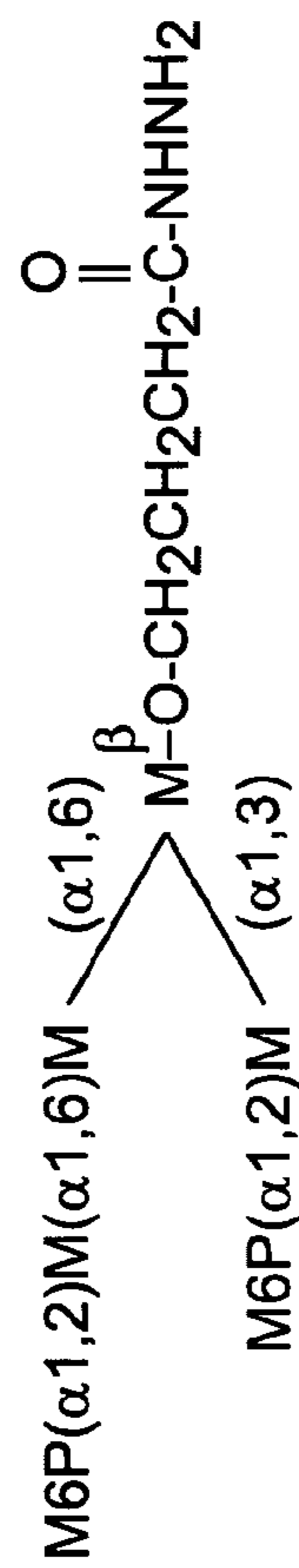


FIG. 13b

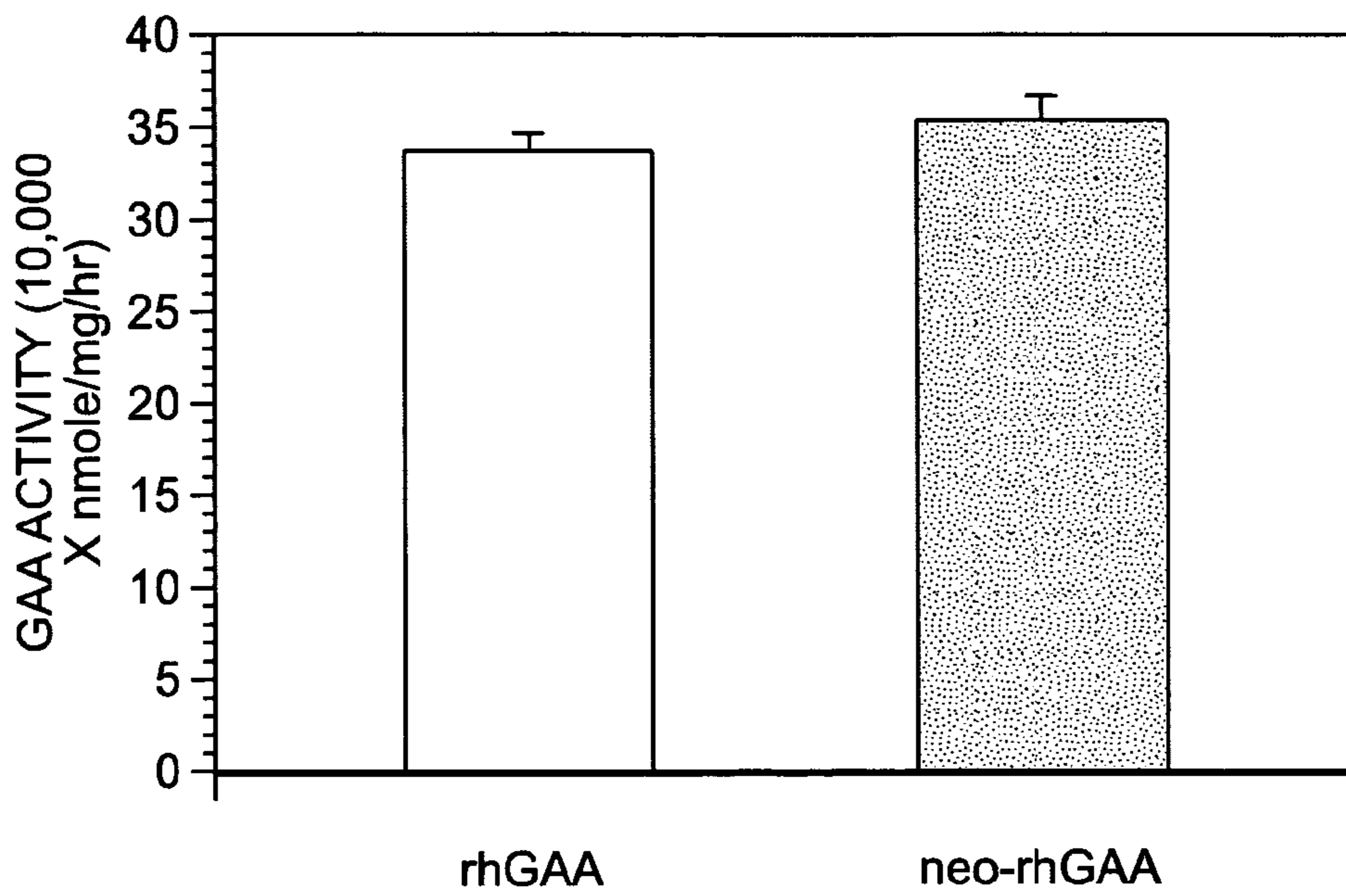


FIG. 14a

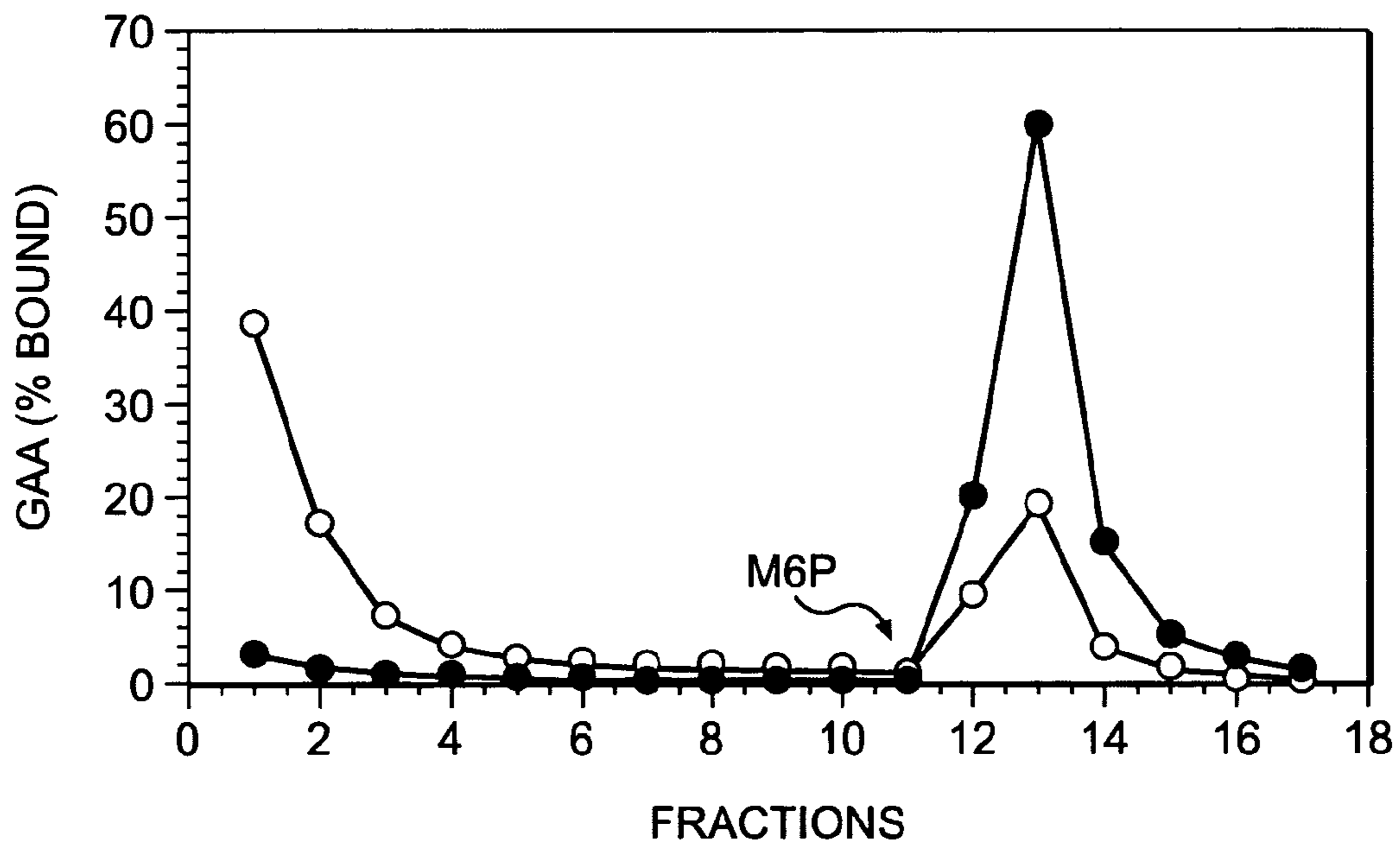


FIG. 14b

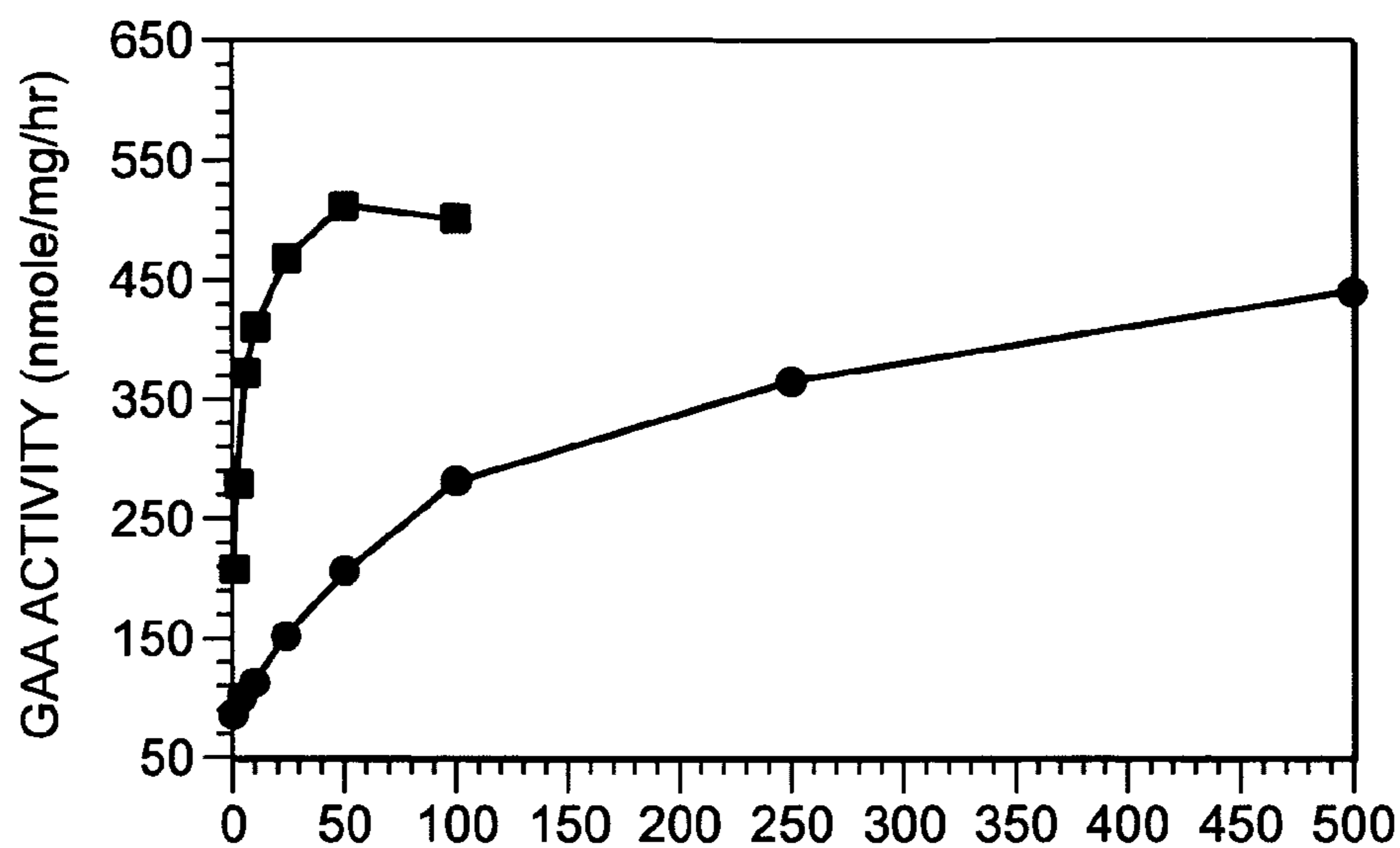


FIG. 15a

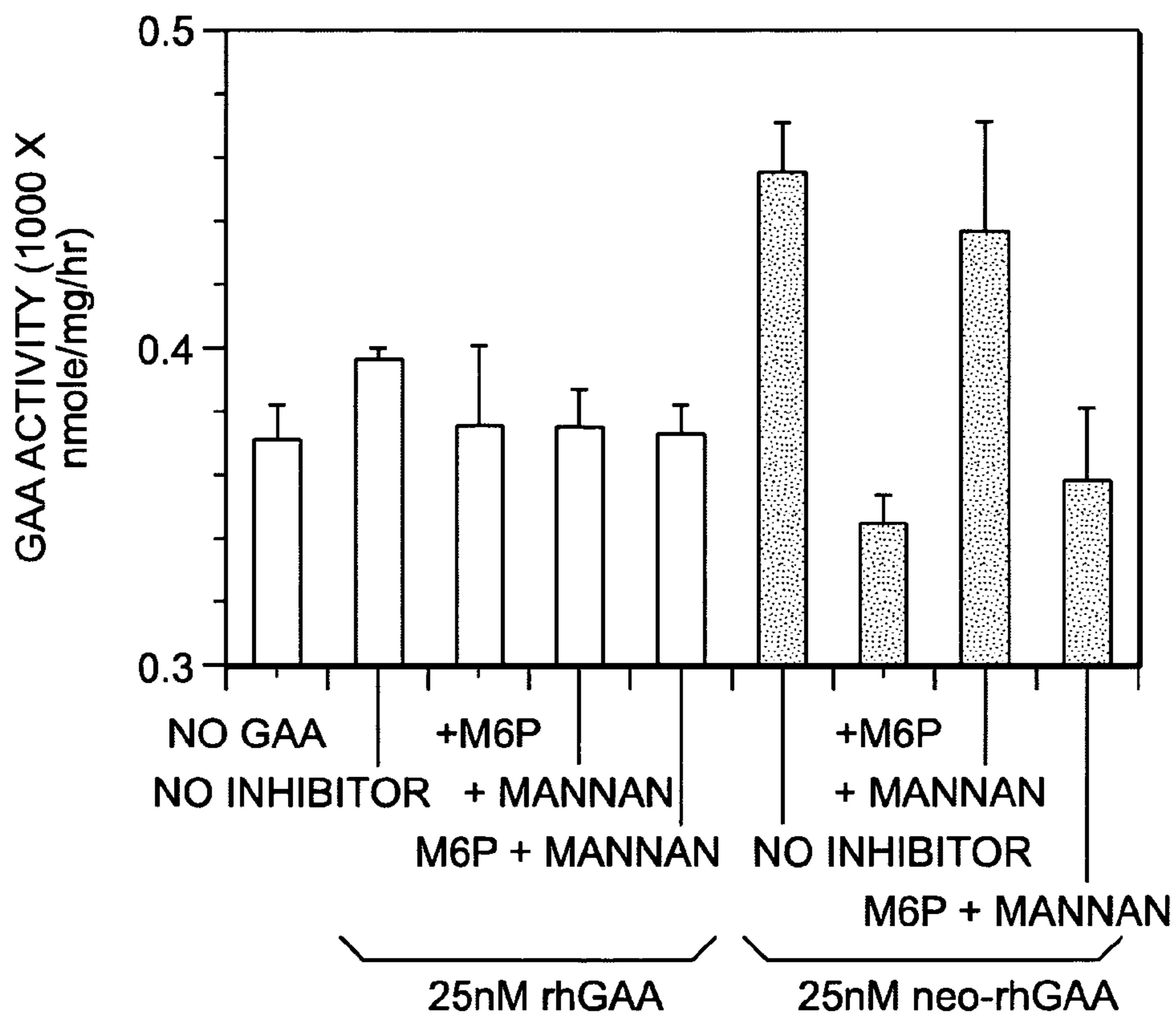


FIG. 15b

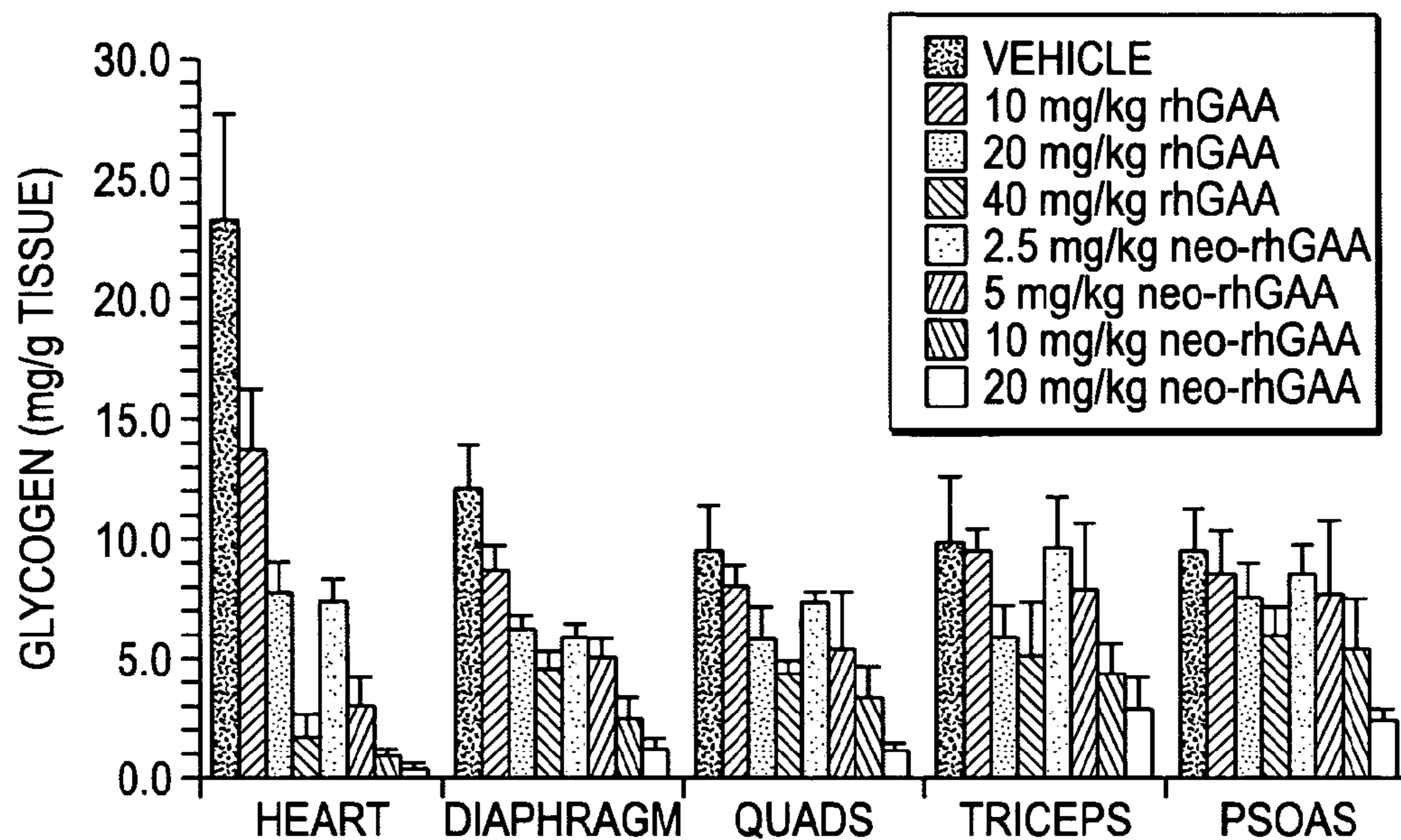


FIG. 16

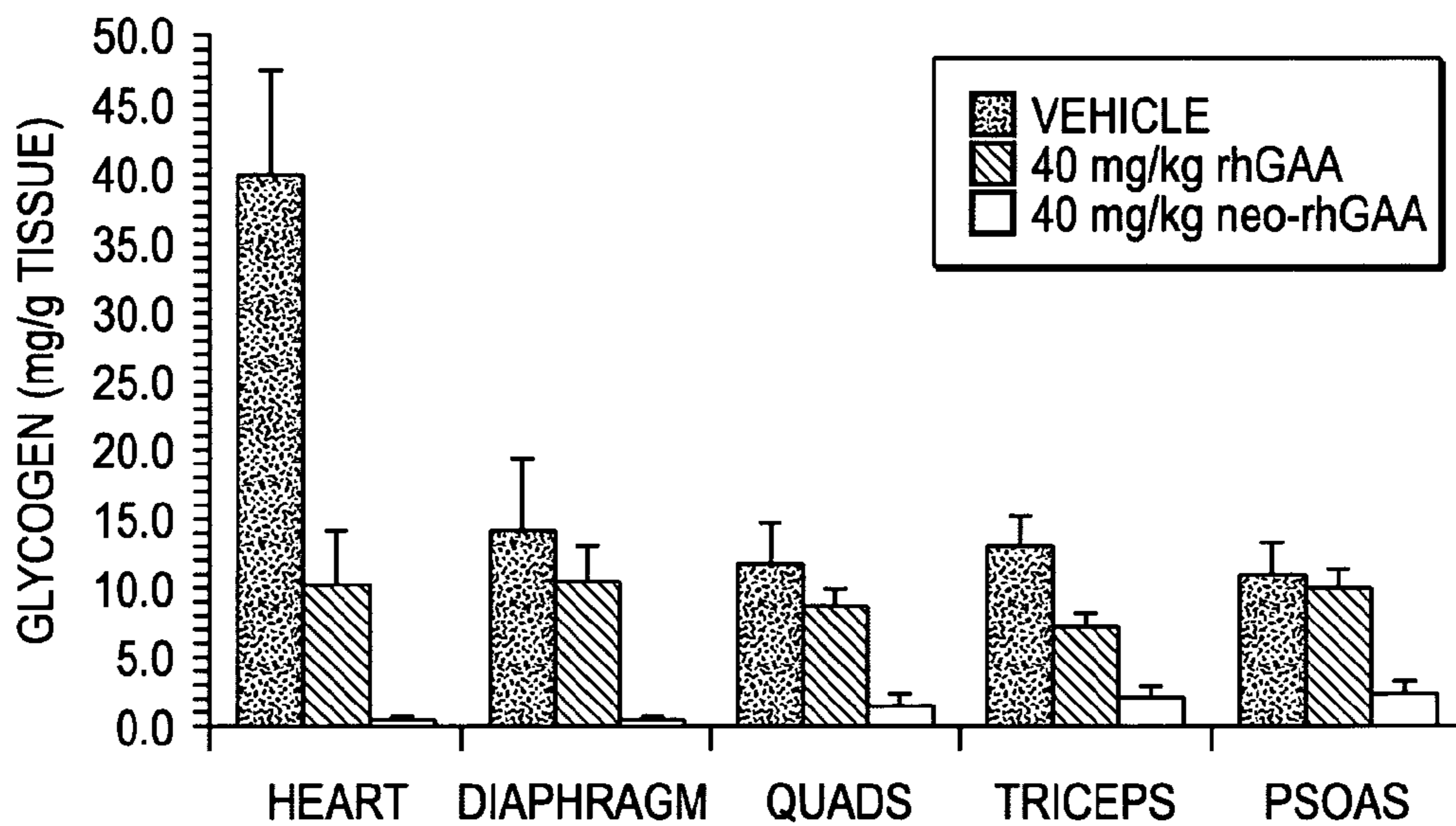


FIG. 17

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**METHODS FOR INTRODUCING MANNOSE
6-PHOSPHATE AND OTHER
OLIGOSACCHARIDES ONTO
GLYCOPROTEINS AND APPLICATIONS
THEREOF**

PRIORITY INFORMATION

This application is a continuation of U.S. application Ser. No. 12/642,383, filed Dec. 18, 2009, which is a continuation of U.S. application Ser. No. 10/943,893, filed Sep. 20, 2004 (now U.S. Pat. No. 7,723,296), which is a continuation-in-part of U.S. patent application Ser. No. 10/051,711, filed Jan. 17, 2002 (now U.S. Pat. No. 7,001,994), which claims the benefit of priority of U.S. provisional patent application No. 60/263,078, filed Jan. 18, 2001 all of which are incorporated herein by reference in their entirety.

BACKGROUND OF THE INVENTION

The present invention relates in general to methods for introducing new oligosaccharides to glycoproteins, and more specifically, to novel methods for conjugating highly phosphorylated mannopyranosyl oligosaccharide derivatives to glycoproteins to form compounds containing mannose-6-phosphate (M6P) for use in medical methods of treatment, and to the compounds thereby produced.

Carbohydrates on glycoproteins play important biological functions in bio-organisms. Well-characterized examples include the selectin-carbohydrate interaction involved in intercellular cell adhesion and sperm/egg interaction (see, e.g., C. G. Gahmberg et al., 27 *APMIS SUPPL.* 39 (1992)), and the mannose 6-phosphate (M6P) dependent lysosomal enzyme targeting pathway (see, e.g., S. Kornfeld and I. Mellman, 5 *ANNUAL REVIEW OF CELL BIOLOGY* 483 (1989)). To facilitate study of the complex functions of carbohydrate structures on glycoproteins, both enzymatic and chemical methods have been developed to remove the carbohydrate glycans from glycoproteins for analysis. A variety of conjugation methods have also been developed to conjugate defined carbohydrates to proteins and then analyze their possible biological functions. The most commonly used conjugation approach involves the use of omega-amino groups of lysine residues. Reactions of amino groups of proteins with compounds such as N-hydroxysuccinimide ester or isothiocyanate derivatives are widely used. Reductive amination, on the other hand, is most commonly used for carbohydrate conjugation to proteins. For example, in the analysis of lysosomal enzyme targeting, coupling of M6P or phosphopentamannose to bovine serum albumin has been achieved through reductive amination (H. Tomoda et al., 213 *CARBOHYDR. RES.* 37 (1991); T. Baba et al., 177 *CARBOHYDR. RES.* 163 (1988)), leading to significant insights regarding the M6P receptor binding to lysosomal enzymes through these M6P conjugated glycoproteins. Reductive amination involves covalently linking the reducing ends of oligosaccharides to amino acid residues in proteins containing free amines (such as lysines), to first form unstable Schiff bases which are then reduced by cyanoborohydride to stable imine bonds.

However, these known conjugation methods are limited in that they are not specific in terms of the amino acid residues involved, and require the direct linkage of chemical conjugates or carbohydrates to amino acid residues, which may cause a change in protein conformation and destroy the biological activity of proteins. For example, when antibody IgG is coupled to various chemical conjugates through amino acid groups, the antibody IgG often loses its immunological activ-

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ity (D. J. O'Shannessy and R. H. Quarles, 7 *J. OF APPL. BIOCHEM.* 347, (1985); T. I. Ghose et al., 93 *METHODS IN ENZYMOLOGY* 280 (1983)). In addition, reductive amination requires high pH and a reductive reagent that may also reduce any disulfide bonds in a protein, thus potentially destroying biological activity.

A more specific approach to introduce certain chemical conjugates onto glycoproteins has been described and involves covalent bond formation between carbonyl (aldehyde) groups generated by mild oxidation of carbohydrates with periodate or galactose oxidase (G. Avigad et al., 237 *J. BIOL. CHEM.* 2736 (1962)) and chemical compounds containing carbonyl-reactive groups. This approach has been used for in vitro attachment of mono- and oligosaccharides to cell surface glycoconjugates of living cells with glycosylhydrazines (M. Tolvanen and C. G. Gahmberg, 261(2) *J. BIOL. CHEM.* 9546 (1986); C. G. Gahmberg and M. Tolvanen, 230 *METHODS IN ENZYMOLOGY* 32 (1994)). Other applications include conjugation of biotin or avidin to glycoproteins with biotin-hydrazide or avidin-hydrazide (Bayer et al., 161 *ANALYTICAL BIOCHEMISTRY* 123 (1987); Bayer et al., 170 *ANALYTICAL BIOCHEMISTRY* 271 (1988); M. Wilchek and E. A. Bayer, 128 *METHODS IN ENZYMOLOGY* 429 (1987)), antibody IgG conjugation for immunodetection (O'Shannessy et al., 8 *IMMUNOLOGY LETTERS* 273 (1984); D. J. O'Shannessy and R. H. Quarles, 7 *J. OF APPL. BIOCHEM.* 347 (1985)) and cancer immunotherapy (J. Singh Kralovec et al., 29 *CANCER IMMUNOLOGY THERAPY* 293 (1989); G. R. Braslawsky et al., 33 *CANCER IMMUNOLOGY THERAPY* 367 (1991)). In these examples, the glycoproteins are treated by mild oxidation with periodate to generate aldehyde groups that then react with hydrazide derivatives. One advantage of this approach for conjugation is that the linkage is through the carbohydrates on the glycoproteins instead of directly involving the protein backbone, thus avoiding inactivation of the glycoproteins' biological activity. Antibodies modified in such a way always retain activity (D. J. O'Shannessy et al., 8 *IMMUNOLOGY LETTERS* 273 (1984); D. J. O'Shannessy and R. H. Quarles, 7 *J. OF APPL. BIOCHEM.* 347 (1985)). In addition, both the oxidation and the covalent bond formation steps are nearly quantitative, and reaction conditions are very mild, thus helping retain the biological activity of the proteins. Retention of biological activity is critical when the modified glycoproteins are to be used for therapeutic purposes.

Lysosomal storage disease describes a class of over 40 genetic disorders (see, e.g., Holton, J. B., *THE INHERITED METABOLIC DISEASES* 205-242 (2nd ed. 1994); Scriver et al., 2 *THE METABOLIC BASIS OF INHERITED DISEASE* (7th ed. 1995)), each resulting from a deficiency of a particular lysosomal enzyme, usually as a result of genetic mutation. Lysosomal enzymes are required to break down protein, glycolipid and carbohydrate metabolites within the lysosomes of cells. When one or more of these enzymes are defective in affected individuals due to inherited mutations, lysosomes in cells of affected individuals accumulate a subset of undigested substrates, largely liposaccharides and carbohydrates as storage materials that are unable to be digested by the defective enzymes. For example, in Gaucher disease, deficiency of beta-glucocerebrosidase causes the accumulation of glucosylceramide; in Fabry disease, the defective alpha-galactosidase A results in accumulation of globotriaosylceramide; in Pompe disease, lack of acid alpha-glucosidase causes accumulation of glyco-gen alpha 1-4 linked oligosaccharides and in Tay-Sachs disease, deficiency of beta-N-acetyl-hexosaminidase leads to accumulation of GM2 ganglioside. Clinically, patients with these syndromes show a variety of symptoms associated with the accumulation of these storage material in the lysosomes,

which eventually affect the normal function of the cells or tissues that result in dysfunction of organs within the human body. The severity of the disease varies with the residual enzyme activity, in severe cases, death can occur early in life.

Lysosomal enzymes, like other secretory proteins, are synthesized and co-translationally translocated into the lumen of the endoplasmic reticulum, where post-translational carbohydrate modification occurs. However, while in transit through the Golgi, they are segregated from the other secretory proteins by specifically acquiring the M6P recognition marker generated by the sequential actions of two enzymes. The first enzyme, UDP-N-acetylglucosamine:Lysosomal-enzyme N-Acetylglucosamine-1-phosphotransferase, transfers the N-acetylglucosamine-1-phosphate to one or more mannose residues on lysosomal enzymes to give rise to phosphodiester intermediates, and the second enzyme, N-acetylglucosamine-1-phosphodiester alpha-N-acetylglucosaminidase, removes the N-acetylglucosamine from the phosphodiester to expose the M6P. Once the lysosomal enzymes with the M6P recognition marker reach the trans-Golgi-network, they are recognized by two specific receptors, the cation-independent mannose 6-phosphate receptor (CI-MPR) and the cation-dependent mannose 6-phosphate receptor (CD-MPR). These receptors with their ligands of lysosomal enzymes are sequestered into clathrin-coated vesicles formed on the trans-Golgi network and transported to endosomes, where the lysosomal enzymes are dissociated from the receptors by the low pH in endosomes and eventually delivered to lysosomes. Some of the lysosomal enzymes are secreted, however, they are captured by binding to the CI-MPR on the cell surface and internalized by the AP-2 mediated clathrin-coated vesicles. Thus, the M6P dependent pathway is the main targeting pathway for lysosomal enzymes, though the M6P independent targeting pathways have been proposed for a few lysosomal enzymes and in certain cell types (see Kornfeld and Mellman, supra).

With the complete elucidation of the lysosomal enzyme targeting pathway and the discovery of lysosomal enzyme deficiencies as the primary cause of lysosomal storage diseases, attempts have been made to treat patients having lysosomal storage diseases by intravenous administration of the missing enzyme, i.e., enzyme replacement therapy, where the injected enzymes are expected to be taken up by target cells through receptor-mediated endocytosis and delivered to lysosomes. Animal models and some clinical trials of enzyme replacement therapy have offered positive results. However, for lysosomal diseases other than Gaucher disease, some evidence suggest that enzyme replacement therapy is most effective when the enzyme being administered has M6P, so that the enzymes can be taken up efficiently by the target cells through the cell surface associated CI-MPR-mediated endocytosis. Gaucher disease, caused by the deficiency of beta-glucocerebrosidase, is an exception because beta-glucocerebrosidase is among the few lysosomal enzymes that are targeted by the M6P independent pathway (see Kornfeld and Mellman, supra). Targeting of beta-glucocerebrosidase for Gaucher disease enzyme replacement therapy to macrophage cells is mediated by remodeling its carbohydrate to expose the core mannose, which binds to the mannose receptor on macrophage cell surface.

While enzyme replacement therapy (ERT) appears promising, supplies of the required enzymes are limited. Lysosomal enzymes can, in theory, be isolated from natural sources such as human placenta or other animal tissues. However, large-scale production of sufficient quantities of enzymes for therapeutic administration is difficult. Further, due to the degradation of carbohydrates in lysosomes, enzymes purified

from tissues do not contain significant amounts of M6P. Alternative approaches include use of recombinant protein expression systems, facilitated by large-scale cell culture or fermentation. For example, lysosomal enzymes have been expressed in Chinese hamster ovary (CHO) cells (V. A. Ioannou et al., 119(5) J. CELL BIOL. 1137 (1992); E. D. Kakkis et al., 5 PROTEIN EXPRESSION PURIFICATION 225 (1994)), insect cells (Y. Chen et al., 20(2) PROTEIN EXPR. PURIF. 228 (2000)), and in transgenic animals or plants (A. G. Bijvoet et al., 8(12) HUM. MOL. GENET. 2145 (1999)). However, lysosomal enzymes purified from recombinant expression systems are also often not well phosphorylated and the extent of M6P phosphorylation varies considerably with different enzymes. Alpha-galactosidase A expressed in CHO cells contains about 20% of phosphorylated enzymes, but only 5% are bisphosphorylated, which is the high-uptake form (F. Matsuura et al., 8(4) GLYCOBIOLOGY 329 (1998)). Alpha-N-acetylglucosaminidase expressed in CHO cells is almost completely lacking M6P phosphorylation (K. Zhao and E. F. Neufeld, 19 PROTEIN EXPR. PURIF. 202 (2000)). In addition, recombinant proteins expressed in plants, insect cells or the methotrophic yeast *pichia pastoris* do not have any M6P phosphorylation because such cells do not have the M6P targeting pathway.

Lysosomal enzymes lacking in M6P phosphorylation compete poorly for receptor-mediated endocytic uptake by target cells and are thus of limited efficacy in enzyme replacement therapy. More specifically, poorly phosphorylated enzymes are effectively removed by the mannose receptor (M. E. Taylor et al., 252 AM. J. PHYSIOL. E690 (1987)) and asialoglycoprotein receptor in liver (Ashwell and Harford, 51 ANN. REV. BIOCHEM 531 (1982)), which can remove most of any administered lysosomal enzymes within a very short period of time.

Against this background, a strong need exists for improved, efficient approaches to phosphorylate lysosomal enzymes, and particularly for methods to modify lysosomal enzymes with M6P. In addition, a need exists for modifying lysosomal enzymes to a high uptake, bisphosphorylated form. Such modified enzymes would be particularly useful for enhancing the efficacy of enzyme replacement therapy for lysosomal storage disease.

BRIEF SUMMARY OF THE INVENTION

Methods of creating neoglycoproteins are provided that increase the cellular uptake of lysosomal enzymes and other glycoproteins by covalently attaching oligosaccharide compositions to oxidized glycans of the glycoproteins through covalent bonds.

Thus, in one embodiment, the invention is directed toward a method for coupling a highly phosphorylated mannopyranosyl oligosaccharide compound to a glycoprotein having at least one glycan, the method comprising derivatizing the highly phosphorylated mannopyranosyl oligosaccharide compound with a chemical compound containing a carbonyl-reactive group; oxidizing the glycoprotein having the at least one glycan to generate at least one aldehyde group on the glycoprotein; and reacting the oxidized glycoprotein having at least one glycan with the derivatized highly phosphorylated mannopyranosyl oligosaccharide compound to form a new compound having a hydrazone bond. The glycoprotein in one embodiment is a lysosomal enzyme.

In one embodiment of the methods, the highly phosphorylated mannopyranosyl oligosaccharide compound contains at least one mannose 6-phosphate group, such as a compound having the formula 6-P-M_n-R wherein:

M is a mannose or mannopyranosyl group;

P is a phosphate group linked to the C-6 position of M;

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R comprises a chemical group containing at least one carbonyl-reactive group; and

n is an integer from 1-15, wherein if $n > 1$, M_n are linked to one another by alpha (1,2), alpha (1,3), alpha (1,4), or alpha (1,6).

Thus, the highly phosphorylated mannopyranosyl oligosaccharide compound includes compounds such as M6P, phosphopentamannose derived from *Hansenula holstii* O-phosphomannan, and 6-P-M-(alpha 1,2)-M(alpha 1,2)-M.

In another embodiment of the methods, the highly phosphorylated mannopyranosyl oligosaccharide compound comprises a compound having the formula $(6\text{-P-M}_x)_m\text{L}_n\text{-R}$ wherein:

M is a mannose or mannopyranosyl group;

L is a mannose or other hexose or other chemical groups;

P is a phosphate group linked to the C-6 position of M;

R comprises a chemical group containing at least one carbonyl-reactive group;

m is an integer from 2-3;

n is an integer from 1-15, wherein if $n > 1$, M_n are linked to one another by alpha (1,2), alpha (1,3), alpha (1,4), or alpha (1,6); and

x is an integer from 1-15.

Thus, the highly phosphorylated mannopyranosyl oligosaccharide compound includes biantennary mannopyranosyl oligosaccharide compounds containing bis-M6P and triantennary mannopyranosyl oligosaccharide compounds containing bis-M6P or tri-M6P.

In one embodiment of the methods, the highly phosphorylated mannopyranosyl oligosaccharide compound can be replaced with other oligosaccharide compositions containing terminal hexoses, such as, for example, a galactose, a mannose, N-acetylglucosamine, or a fucose, which can bind to different carbohydrate-binding receptors other than CI-MPR.

In another embodiment of the methods, the chemical compound containing carbonyl-reactive group includes any compound that reacts with carbonyl groups to form a hydrazone bond. Such compounds include hydrazines, hydrazides, aminoxylys, and semicarbozides and the like.

In addition, the methods further encompass reducing the compound having a hydrazone bond with a reducing agent such as cyanoborohydride to form a compound having an imine bond.

The invention is further directed toward chemical compounds produced by coupling a first chemical compound having at least one carbonyl group (aldehyde or ketone) to a second chemical compound comprising a phosphorylated mannopyranosyl oligosaccharide derivative, according to the coupling methods described and herein, i.e., by derivatizing the highly phosphorylated mannopyranosyl oligosaccharide compound with a chemical compound containing a carbonyl-reactive group; and reacting to the first chemical compound having at least one carbonyl group with the derivatized highly phosphorylated mannopyranosyl oligosaccharide compound to form a new compound having a hydrazone bond. Such compounds include antiviral compounds and gene targeting delivery agents.

In another embodiment, the invention is directed toward methods of treating lysosomal storage disease in a subject in need thereof, the methods including administering to the subject an effective amount of a glycoprotein coupled according to the methods described herein to a second chemical compound comprising a highly phosphorylated mannopyranosyl oligosaccharide derivative containing at least one mannose 6-phosphate group. Lysosomal storage diseases that are treated with a glycoprotein modified according to the methods described herein include Fabry disease, Pompe disease,

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and others (for a complete list, see J. B. Holton, *THE INHERITED METABOLIC DISEASES* 205-242 (2d ed. 1994); C. R. Scriver et al., *THE METABOLIC BASIS OF INHERITED DISEASE* (7th ed. 1995)).

The present methods couple highly phosphorylated mannopyranosyl oligosaccharides containing M6P, to glycoproteins, so that cellular uptake of such glycoproteins is enhanced without destroying their biological activity. As such, the methods and compounds produced thereby are especially useful where in medical treatment methods that benefit from enhanced uptake forms of glycoproteins, such as in enzyme replacement therapy for the treatment of lysosomal storage diseases.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic representation of a conjugation method.

FIGS. 2A-2C are schematic representations of alternative oxidation methods used in the conjugation methods.

FIG. 3 is a SDS-PAGE analysis of different avidins before and after phosphopentamannose-hydrazine conjugation.

FIG. 4 is a CI-MPR binding analysis of untreated avidin and oxidized avidin conjugated with phosphopentamannose-hydrazine.

FIG. 5 is a bar graph showing enzymatic activity of beta-glucuronidase after different treatments including after conjugation.

FIG. 6 is a bar graph comparing CI-MPR binding of untreated and oxidized phosphopentamannose-conjugated beta-glucuronidase.

FIG. 7 depicts GAA activity, measured in nmole/hour, in fractions obtained from a CI-MPR column following binding of recombinant human GAA (shown by open circles), and phosphopentamannose-conjugated rhGAA (shown by closed circles) to the CI-MPR column.

FIG. 8A depicts the results of a chromatographic analysis of oligosaccharides released following digestion of α -galactosidase A with endoglycosidase H. FIG. 8B depicts the results of a chromatographic analysis of oligosaccharides following purification of the M6P-containing fraction over a QAE column by dionex column chromatography.

FIG. 9 depicts GAA activity in fractions obtained following binding of rhGAA (shown by open circles), modified rhGAA (neo-rhGAA) (shown by closed circles) and periodate-treated rhGAA (shown by open squares) to a CI-MPR column.

FIG. 10 depicts a graph showing the in vitro uptake of the modified rhGAA (neo-rhGAA) into L6 myoblasts. Open circles represent increasing amounts of rhGAA and closed squares represent increasing amounts of modified rhGAA (neo-rhGAA). Endogenous GAA levels were subtracted from the data presented.

FIGS. 11A-11D depict graphs representing the level of glycogen in heart (11C), skeletal muscles (Quadriceps in 11A; Triceps in 11B), and diaphragm (11D) of Pompe mice treated with varying doses of either rhGAA or neo-rhGAA.

FIG. 12 depicts a bar graph showing the percentage of area occupied by glycogen in quadriceps muscle of Pompe mice treated with vehicle control (A); 10 mg/kg rhGAA (B); 50 mg/kg rhGAA (C); and 20 mg/kg neo-rhGAA (D).

FIG. 13A is a schematic representation of the naturally occurring high mannose oligosaccharide (Man9) from which the synthetic bis-M6P glycan, shown in FIG. 13B, is derived.

FIG. 14A depicts GAA activity of the unmodified rhGAA and modified neo-rhGAA, conjugated with synthetic bis-M6P. FIG. 14B depicts GAA activity in fractions obtained

following binding of rhGAA (open circles) and synthetic bis-M6P conjugated rhGAA (closed circles) to a CI-MPR column.

FIGS. 15A and 15B depict results of in vitro uptake assays in L6 myoblasts and macrophages, respectively. FIG. 15A shows in vitro uptake of rhGAA (closed circles) and neo-rhGAA (closed squares) into L6 myoblasts, as measured by GAA activity in cell lysates following treatment with rhGAA or neo-rhGAA. FIG. 15B depicts a bar graph showing the results of an in vitro uptake experiment in macrophages, treated either with rhGAA or neo-rhGAA, and further in presence or absence of M6P and/or mannan. As in the case of myoblasts, in vitro uptake was measured by assaying for GAA activity in cell lysates.

FIG. 16 is a bar graph showing glycogen levels, as assayed using the Amplex Red glucose assay, in representative tissues of young Pompe mice (4-5 months of age) following treatment with varying doses of vehicle alone, unmodified rhGAA or neo-rhGAA.

FIG. 17 is a bar graph showing glycogen levels, as assayed using the Amplex Red glucose assay, in representative tissues of old Pompe mice (13 months of age) following treatment with vehicle alone, 40 mg/kg of unmodified rhGAA or 40 mg/kg of neo-rhGAA.

DETAILED DESCRIPTION OF THE INVENTION

The present methods couple highly phosphorylated mannopyranosyl oligosaccharides containing M6P to glycoproteins, such as, for example, avidin and lysosomal enzymes beta-glucuronidase and acid alpha-glucosidase, without destroying their biological activity. The present methods thus provide a novel approach to introduce highly phosphorylated mannosyloligosaccharide derivatives to lysosomal enzymes and other glycoproteins. In exemplary embodiments, the methods and compounds described herein are useful for modifying lysosomal enzymes produced by recombinant protein expression system with M6P, thus to enhance the efficacy of enzyme replacement therapy of lysosomal storage diseases.

As used herein, the term "highly phosphorylated" refers to a characteristic of oligosaccharides that are coupled to glycoproteins or to other compounds according to the methods described herein, wherein the oligosaccharides contain at least one M6P group and, in an exemplary embodiment, two or more M6P groups.

As used herein, the term "effective" refers to a characteristic of an amount of a compound produced according to the methods of the present invention, wherein the amount of the compound has the effect of preventing or reducing a deficiency of a lysosomal enzyme in a subject. The lysosomal enzyme deficiency is, for example, the result of a genetic mutation in a human that produces a lysosomal storage disease. Such diseases include, for example, Gaucher disease wherein a deficiency of beta-glucocerebrosidase results in the accumulation of glucosylceramide, Fabry disease wherein a deficiency of alpha-galactosidase A results in accumulation of globotriaosylceramide, Pompe disease wherein a deficiency of acid alpha-glucosidase results in accumulation of glycogen alpha 1-4-linked oligosaccharides, and Tay-Sachs disease wherein a deficiency of beta-N-acetyl-hexosaminidase leads to accumulation of GM2 ganglioside, and other diseases including Hurler or Hurler-Scheie disease, Krabbe disease, Metachromatic leukodystrophy, Hunter disease, Sanfilippo A and B disease, Morquio A disease, and Maroteaux-Lamy disease and other diseases (see Holton, J. B., 1994, *THE INHERITED METABOLIC DISEASES*, 2nd Edition; Scriver

et al., 1995, *THE METABOLIC BASIS OF INHERITED DISEASE*, Volume 2, 7th Edition, which are herein incorporated by reference).

Thus, in an exemplary embodiment, a method for coupling a highly phosphorylated mannopyranosyl oligosaccharide compound to a glycoprotein having at least one glycan includes derivatizing the highly phosphorylated mannopyranosyl oligosaccharide compound with a chemical compound containing a carbonyl-reactive group; oxidizing the glycoprotein having the at least one glycan to generate at least one aldehyde group on the glycoprotein; and reacting the oxidized glycoprotein with the derivatized highly phosphorylated mannopyranosyl oligosaccharide compound to form a new compound having a hydrazone bond. Oxidizing the glycoprotein having the at least one glycan is accomplished using, for example, periodate or galactose oxidase.

The glycoprotein having the at least one glycan is, for example, a glycoprotein such as a lysosomal enzyme. The glycoprotein can be derived from a variety of sources. In the case of lysosomal enzymes, natural sources include human placenta and other animal tissues. Alternatively, lysosomal enzymes that are especially useful for modification according to the present methods are produced by recombinant protein expression systems, including yeast, mammalian cells, insect cells, plant cells and transgenic animals or plants.

The chemical compound containing the carbonyl-reactive group is any compound that reacts with carbonyl groups to form a hydrazone bond. Suitable such compounds include, for example, hydrazine, hydrazide, aminoxy, and semicarbazide and the like.

In one embodiment, the highly phosphorylated mannopyranosyl oligosaccharide compound contains at least one mannose 6-phosphate group, such as an oligosaccharide of the formula 6-P-M_n-R wherein:

M is a mannose or mannopyranosyl group;

P is a phosphate group linked to the C-6 position of M;

R comprises a chemical group containing at least one carbonyl-reactive group; and

n is an integer from 1-15, wherein if n>1, M_n are linked to one another by alpha (1,2), alpha (1,3), alpha (1,4), or alpha (1,6).

Thus, the highly phosphorylated mannopyranosyl oligosaccharide compound includes compounds such as M6P, phosphopentamannose derived from *Hansenula holstii* O-phosphomannan, and 6-P-M-(alpha 1,2)-M(alpha 1,2)-M.

In an exemplary embodiment, the oligosaccharides are those biantennary and triantennary oligosaccharides that have the formula of (6-P-M_x)_mL_n-R wherein:

M is a mannose or mannopyranosyl group;

L is a mannose or other hexose or other chemical groups;

P is a phosphate group linked to the C-6 position of M;

R comprises a chemical group containing at least one carbonyl-reactive group;

m is an integer from 2-3;

n is an integer from 1-15, wherein if n>1, M_n are linked to one another by alpha (1,2), alpha (1,3), alpha (1,4), or alpha (1,6); and

x is an integer from 1-15.

Thus, the highly phosphorylated mannopyranosyl oligosaccharide compound includes biantennary mannopyranosyl oligosaccharide compounds containing bis-M6P and triantennary mannopyranosyl oligosaccharide compounds

hydrophilic, cellular compartment-specific anti-viral drugs. Anti-viral drugs with M6P are taken up by the cells through MPR-mediated endocytosis to concentrate in endosomes where virus entry occurs, thus subjecting early stage viral infection to attack by the antiviral compound before viral replication, resulting in improved therapeutic value. A similar approach of involving coupling of AZT to mannosylated BSA, which can be taken up by the mannose-receptor, has been shown to have higher anti-viral activity than the AZT parental drug (G. Molema et al., 34(3) J. MEDICINAL CHEM. 1137 (1991)).

In another embodiment of this invention, the methods are used to modify oligonucleotides useful in gene therapy targeted to correct point mutation in genes. More specifically, the methods are used to modify RNA-DNA chimeric oligonucleotides that are used to repair one or two base pair alterations in the genome of mammalian cells (E. B. Kmiec, 17 ADV. DRUG DELIVERY REVIEWS 333 (1995); K. Yoon et al., 93 PROC. NATL. ACAD. SCI. 2071 (1996)). Such a strategy has been used, for example, to correct the mutation responsible for sickle cell anemia in vitro (A. Cole-Strauss et al., 273 SCIENCE 1386 (1996)), to mutate the rat factor IX gene and UGT in rat liver in vivo (B. T. Kren et al., 4 NATURE MEDICINE 285 (1998); B. T. Kren et al., 96(18) PROC. NATL. ACAD. SCI. 10349 (1999); P. Bandyopadhyay et al., 274 J. BIOL. CHEM. 10163 (2000)) and to correct dystrophin in mdx mouse muscle (T. A. Rando et al., 97(10) PROC. NATL. ACAD. SCI. 5363 (2000)). A critical step for success with this strategy is to deliver the oligonucleotides to target cells with high efficiency. The percentage of gene conversion correlates with the efficiency of oligonucleotide delivery, which is enhanced by modifying polycations or liposome with lactose for the asialoglycoprotein receptor on liver hepatocytes (Kren et al. 1998, supra; Kren et al. 1999; supra; Bandyopadhyay et al., supra). In contrast, for the mdx mouse dystrophin, only the muscle near the injection site is converted (Rando et al., supra), presumably because only cells nearby the injection site take up the injected oligonucleotides. Thus, an efficient and general delivery approach of the oligonucleotides for a variety of target cells in vivo is especially useful for expanding the application of such gene therapies. Accordingly, the methods described herein permit M6P modification to provide improved delivery of oligonucleotides to target cells by enhancing MPR-mediated uptake. MPRs are present on a wide variety of cells in vivo and MPR-mediated endocytic process is as efficient an uptake process as the asialoglycoprotein receptor-mediated endocytosis on hepatocytes in liver. PEI/liposome delivery systems employed for the aforementioned oligonucleotides, or the oligonucleotides can be easily modified with M6P or M6P oligosaccharide derivatives, thus to expand the target cell types in vivo for gene-targeted therapy.

The following examples provide illustrative embodiments of the invention. One of ordinary skill in the art will recognize the numerous modifications and variations that may be performed without altering the spirit and scope of the present invention. Such modifications and variations are encompassed within the scope of the invention. The examples do not in any way limit the invention.

EXAMPLES

Example 1

Synthesis of Phosphopentamannose-Hydrazine Derivatives

Phosphopentamannose was prepared from phosphomanan obtained from Dr. M. E. Slodki, Northern Regional Research

Laboratory, U.S. department of agriculture, Peoria, Ill. Phosphopentamannose was prepared essentially as described by M. E. Slodki (1962) and has the following structure: 6-P-M (alpha 1,3)-M(alpha 1,3)-M(alpha 1,3)-M(alpha 1,2)-M.

100 mg of lyophilized powder of phosphopentamannose was added into a glass tube, to which 3 ml of anhydrous hydrazine was added. The tube was filled with nitrogen gas, capped with a tight fitting cap, and wrapped with parafilm. The reaction was proceeded at room temperature for 6-18 hours, after which the hydrazine was evaporated under vacuum while the hydrazine was absorbed through a bottle of sulfuric acid. 2 ml of toluene was added and removed by a stream of nitrogen gas to get rid of the residual hydrazine (Tolvanen and Gahmberg, 1986, supra; Gahmberg and Tolvanen, 1994, supra). Phosphopentamannosyl-hydrazine (PPMH) was dissolved in 2 ml of water and dialyzed against 4 liters of 10 mM phosphate buffer (pH 7.0) overnight at 4° C., after which the sample was collected and lyophilized.

Example 2

Coupling of Phosphopentamannose-Hydrazine to Avidin

A. Oxidation of Avidin

1 ml of 2.5 mg/ml of avidin (obtained from Sigma or Pierce) were oxidized with 10 mM sodium periodate in 100 mM sodium acetate (pH 5.6) for 30 minutes at 4° C. in the dark. After which 25 µl of glycerol were added and the sample was incubated on ice for 15 minutes to consume the excess sodium periodate. Samples were then dialyzed overnight against 100 mM sodium acetate (pH 5.6) at 4° C. 0.5 ml of 2.5 mg/ml avidin without periodate oxidation were processed the same way as untreated control. Samples after dialysis were collected and stored at 4 or -20° C. until use.

B. Coupling of Phosphopentamannose-Hydrazine to Oxidized Avidin

200 µl of untreated or oxidized avidin (2.5 mg/ml) were mixed with 1 mg of phosphopentamannose-hydrazine dissolved in 20 µl of 100 mM sodium acetate buffer (pH 5.6) and incubated at 37° C. for 1 hour. The samples were dialyzed against 2 liters of CI-MPR binding buffer (50 mM imidazole, 150 mM NaCl, 1 mM EDTA, 0.5 mM MgCl₂, 1 mM beta-glycerol phosphate, 0.025% Triton X-100, pH 7.0) overnight at 4° C. Samples were collected after dialysis. 10 µl of untreated avidin/conjugated, oxidized avidin control without conjugation, oxidized avidin/conjugated samples were boiled in SDS sample buffer and separated on 12% SDS-gel to see if there is any mobility shift. 50 µl of the samples are subjected to the CI-MPR binding test. The remaining samples are stored at -20° C. until use.

FIG. 3 is a SDS-PAGE analysis of different avidins before and after phosphopentamannose-hydrazine conjugation. Lane 1 shows the results for untreated avidin with conjugation. Lane 2 shows the results for oxidized avidin without conjugation. Lane 3 shows the results for oxidized avidin with phosphopentamannose conjugation. Only Lane 3 shows some avidin retardation in migration, indicating conjugation has occurred. As shown in FIG. 3, there is a clear shift of molecular weight in the oxidized avidin/conjugated sample compare to the untreated avidin/conjugated or oxidized avidin without conjugation controls, indicating that the oxidized avidins are coupled to phosphopentamannose-hydrazine. The molecular weight shift is about 1-4 kDa, suggesting 1-4 phosphopentamannose were coupled to one monomer of avidin.

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C. Binding of Unconjugated Avidin and Conjugated Avidin to CI-MPR Column

100 μ g of untreated avidin/conjugated (unconjugated) and oxidized avidin/conjugated in 0.5 ml CI-MPR binding buffer were passed through a CI-MPR column 5 times, and the final passage was collected as flow-through. The column was washed with 8 volumes of binding buffer, an aliquot of the final wash was collected, and finally the bound avidin were eluted with 0.5 ml of 5 mM M6P in binding buffer. 20 μ l of the flow through, the final wash and the eluted samples were separated on SDS-gel as described for FIG. 3.

FIG. 4 is a CI-MPR binding analysis of untreated avidin and oxidized avidin conjugated with phosphopentamannose-hydrazine. As is shown in FIG. 4, none of the untreated/conjugated avidin binds to the CI-MPR column, whereas all the oxidized avidin/conjugated binds to the CI-MPR column, indicating the efficiency of coupling of phosphopentamannose-hydrazine to oxidized avidin is nearly 100%. The oxidized avidin/unconjugated sample, as the untreated avidin, also does not bind to CI-MPR column (data not shown), indicating the coupling procedure is specific.

Example 3

Conjugation of Phosphopentamannose-Hydrazine to Beta-Glucuronidase does not Inactivate the Enzyme

One major concern about the conjugation is that lysosomal enzymes conjugated in such a way must retain enzymatic activity, preferably full activity. While the avidin conjugation result clearly has shown that the coupling process is highly efficient, whether the coupling process affect its biological activity is unknown, in particular, avidin is a stable protein, not an enzyme. Therefore in the following example, lysosomal enzyme beta-glucuronidase isolated from bovine liver (50,000 U/mg, not completely pure, purchased from Sigma) was used.

A. Oxidation

6 mg of beta-glucuronidase were dissolved in 1.5 ml of water, 1.3 ml of the material (4 mg/ml) were dialyzed against 100 mM NaAc (pH 5.6) overnight at 4° C. 200 μ l of the rest of the sample were kept at 4° C. as water-control.

Of the sodium acetate dialyzed beta-glucuronidase, 0.5 ml were kept as untreated-dialyzed material, 0.8 ml were oxidized with 10 mM sodium periodate at 4° C. for 30 minutes. After which 20 μ l glycerol were added and the sample mixed on ice for 10 minutes to decompose all the excess sodium periodate, then the oxidized material was dialyzed against 1 liter 100 mM sodium acetate overnight. 0.4 ml of the sample was kept at 4° C. as oxidized-dialyzed control. The other 0.5 ml of sample were used for phosphopentamannose-hydrazine coupling.

B. Coupling

3 mg of phosphopentamannose-hydrazine were dissolved in 25 μ l of 100 mM NaAc (pH, 5.6) and mixed with 0.5 ml oxidized beta-glucuronidase (4 mg/ml) and incubated at 37° C. for 2 hours, the coupled sample was dialyzed against CI-MPR binding buffer overnight.

C. Enzymatic Activity of Variously Treated Beta-Glucuronidase

To 200 μ l of 100 mM p-nitrophenyl beta-glucuronide in 100 mM sodium acetate (pH 5.0), 15 μ l of water as negative control, 15 μ l of beta-glucuronidase dissolved in water, 15 μ l of sodium acetate dialyzed-untreated beta-glucuronidase, 15 μ l of oxidized-dialyzed beta-glucuronidase and 15 μ l of oxidized beta-glucuronidase+phosphopentamannose-hydrazine

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were added. After incubation at 37° C. for 1 hr, 200 μ l of 200 mM glycine (pH 10.4) were added. OD of each sample was measured at 400 nm.

The results of one such experiment are described in Table 1.

TABLE 1

Sample	OD at 400 nM
15 μ l water	0.00
15 μ l beta-glucuronidase dissolved in water	1.40
15 μ l untreated NaAc dialyzed beta-glucuronidase	1.37
15 μ l oxidized beta-glucuronidase NaAc-dialyzed	1.43
15 μ l oxidized beta-glucuronidase plus phosphopentamannose	1.44

FIG. 5 is a bar graph showing enzymatic activity of beta-glucuronidase after different treatments including after conjugation. 1 is H₂O control; 2, beta-glucuronidase dissolved in H₂O; 3, beta-glucuronidase dialyzed against NaAc (pH 5.6); 4, oxidized beta-glucuronidase dialyzed against NaAc, and 5, oxidized beta-glucuronidase conjugated with phosphopentamannose-hydrazine. The results represent an average of three experiments and indicate nearly equal beta-glucuronidase activity in all samples. Thus, the overall procedure did not appear to inactivate the beta-glucuronidase. This result is expected because the coupling procedure does not involve the protein backbone, and thus should not affect the overall protein conformation.

D. CI-MPR Binding and Beta-Glucuronidase Assay

100 μ l of untreated beta-glucuronidase (CI-MPR binding buffer dialyzed) and 100 μ l of oxidized beta-glucuronidase+phosphopentamannose-hydrazine conjugated (CI-MPR binding buffer dialyzed) were mixed with 400 μ l of CI-MPR binding buffer (pH 7.0). 50 μ l of each sample were saved as starting material for late beta-glucuronidase assay.

450 μ l of each sample were passed over a 2 ml CI-MPR column (pre-equilibrated with CI-MPR binding buffer) 5 times. The flow-through of each sample was saved. The column was washed with 8 volumes of CI-MPR binding buffer, the last 0.5 ml was saved as final wash. Finally, the column was eluted with 5 mM M6P in CI-MPR binding buffer by passing over the column 4 times, the eluates were collected as M6P elutions. Therefore each sample has 3 fractions plus the starting material controls. The beta-glucuronidase assay is described below.

To 200 μ l of 100 mM p-nitrophenyl glucuronide in 100 mM sodium acetate buffer (pH 5.0),

30 μ l of water,

30 μ l of untreated beta-glucuronidase column starting material,

30 μ l of untreated beta-glucuronidase flow-through,

30 μ l of untreated beta-glucuronidase wash,

30 μ l of untreated beta-glucuronidase M6P elution,

30 μ l of oxidized beta-glucuronidase+PPMH (imidazole) column starting material,

30 μ l of untreated beta-glucuronidase+PPMH flow-through,

30 μ l of untreated beta-glucuronidase+PPMH wash,

30 μ l of untreated beta-glucuronidase+PPMH M6P elution,

were added, the samples were incubated at 37° C. for 1 hour. 200 μ l of 200 mM glycine (pH 10.4) was added to each sample to stop the reaction and OD400 nm was measured.

The results from one such experiment are summarized in Table 2.

TABLE 2

Sample	O.D. at 400 nm
30 μ l water	0.00
30 μ l untreated beta-glucuronidase column starting material	1.43
30 μ l untreated beta-glucuronidase flow-through	1.36
30 μ l untreated beta-glucuronidase wash	0.00
30 μ l untreated beta-glucuronidase M6P elution	0.00
30 μ l untreated beta-glucuronidase + PPMH column starting material	1.41
30 μ l untreated beta-glucuronidase + PPMH flow-through	0.27
30 μ l untreated beta-glucuronidase + PPMH wash	0.00
30 μ l untreated beta-glucuronidase + PPMH M6P elution	0.06

FIG. 6 is a bar graph comparing the CI-MPR binding results for untreated and oxidized phosphopentamannose-conjugated beta-glucuronidase. For the untreated material, nearly 100% of the starting activity was in the flow through, nothing was in the final 0.5 ml wash and M6P elution fractions. However, for the oxidized beta-glucuronidase+phosphopentamannose-hydrazine sample, only 19% of the starting activity was in the flow through, nothing in the final 0.5 ml wash and about 5% was in the M6P elution fraction.

For the untreated sample, the total beta-glucuronidase activities in the starting material and in the flow-through are about equal so there is no clear loss of sample during the column binding. However, for the oxidized/conjugated beta-glucuronidase sample, the total activity of the flow-through and the M6P elution does not add up to the total activity of the starting material. This is not due to the loss of enzymatic activity by oxidation (FIG. 5), but due to the fact that the oxidized beta-glucuronidase conjugated to phosphopentamannose has relatively low binding affinity to CI-MPR (J. Distler et al., supra), especially when one oxidized glycan was conjugated to only one phosphopentamannose-hydrazine due to steric hindrance of the vicinal aldehyde groups. The binding of oligomannosyl phosphate substrates to CI-MPR column has been well characterized (P. Y. Tong et al., 264(14) J. BIOL. CHEM. 1962 (1989); J. Distler et al., supra). The monophosphate form of oligomannosyl substrate binds to CI-MPR column with low-affinity compare to the bisphosphorylated substrate, with large portion of the monophosphate substrate being eluted during the washing step and the rest eluted with M6P, whereas the bisphosphorylated substrate can only be eluted with M6P (P. Y. Tong et al., supra). Therefore, the most likely possibility is that the oxidized beta-glucuronidase conjugated with phosphopentamannose-hydrazine may just behave like the substrate with only one monophosphate and being lost in the first few volumes of washing buffer.

Example 4

Preparation of Modified Recombinant Human Acid α -Glucosidase (Neo-rhGAA)

A. Endoglycosidase H Digestion of α -Galactosidase A

One gram of purified recombinant human α -galactosidase A (Genzyme Corp., Cambridge, Mass.) was reconstituted in 180 ml of deionized water and dialyzed twice against 4 liters of 25 mM acetate buffer (pH 5.6) for 18 hours. The dialyzed α -galactosidase A was subsequently mixed with 20 ml of 0.5

M citrate buffer (pH 5.5) containing 1% β -mercaptoethanol. Digestion was performed with 50,000 units of endoglycosidase Hf (New England Biolabs, Beverly, Mass.) at 37° C. for 4 hours or until completion, as determined by SDS-PAGE. Following digestion, the sample was filtered through a Centriprep-20 column with a molecular weight cut off of 5000 Da (Millipore, Bedford, Mass.). The filtrate containing the released oligosaccharide was collected and dialyzed against three changes of 4 liters of deionized water at 4° C.

B. Isolation and Derivatization of M6P-Containing Oligosaccharide

M6P-containing oligosaccharides were released from recombinant α -galactosidase A (Genzyme Corp) by digesting with endoglycosidase Hf (New England Biolabs) and purified according to the method of Varki and Kornfeld (255 J. BIOL. CHEM. 10847-10858 (1980)) with minor modifications. The dialyzed oligosaccharides were adjusted to 2 mM Tris and then loaded onto a 20 ml QAE-sephadex A column that had been equilibrated with the same buffer at a flow rate of 1.5 ml/min. The column was washed sequentially with 2 mM Tris containing 20 mM and 70 mM NaCl, and the M6P-containing oligosaccharides were eluted with 2 mM Tris containing 200 mM NaCl. The purified M6P-containing oligosaccharides and the phosphopentamannose were derivatized to glycosylhydrazines using the method of Tolvanen and Gahmberg. (261 J. BIOL. CHEM. 9546-9551 (1986)).

C. Chemical Conjugation of Derivatized M6P-Containing Oligosaccharides onto rhGAA

Recombinant human acid α -glucosidase (rhGAA) was dialyzed twice against 2 liters of 0.1 M sodium acetate (pH 5.6) for 18 hours at 4° C. The nucleotide sequence of rhGAA is shown in SEQ ID NO:1 and the amino acid sequence of rhGAA is shown in SEQ ID NO:2. The dialyzed rhGAA (5 mg/ml) was oxidized with 2 mM sodium meta-periodate for 30 minutes on ice. Excess sodium meta-periodate was removed by the addition of 0.5 ml of 50% glycerol and incubation on ice for 15 minutes. The oxidized enzyme was then dialyzed against 2 liters of 0.1 M sodium acetate (pH 5.6). Fifty mg aliquots of the oxidized rhGAA were conjugated to 10 mg of hydrazine-derivatized M6P-containing oligosaccharides or 20 mg of phosphopentamannose by mixing and incubating at 37° C. for 2 hours. After conjugation, both the M6P- and phosphopentamannose-conjugated rhGAA samples were dialyzed against 4 liters of 25 mM sodium phosphate buffer (pH 6.75) containing 1% mannitol and 0.005% Tween-80 for 18 hours at 4° C. and then sterile filtered. The samples were aliquoted, snap-frozen on dry ice and stored at -80° C. until further analysis.

Example 5

Process for Chemically Conjugating M6P-Containing Oligosaccharides onto rhGAA Did not Affect its Enzymatic Activity

Direct chemical conjugation of oligosaccharides onto a protein backbone via reductive amidation or maleimide chemistries frequently requires prolonged incubations at neutral to alkaline pH. These reaction conditions are destabilizing to lysosomal enzymes such as GAA that have optimal activities at acidic pH. In order to minimize the inactivation of GAA, a conjugation method was used which employed a condensation reaction between an aldehyde group and a hydrazine to form a hydrozone bond. In this method, M6P-containing oligosaccharides were derivatized to glycosylhydrazines and then conjugated (at acidic pH) to rhGAA, the sialic acids of which had been oxidized with periodate to

aldehydes. Conjugating the M6P-containing moieties directly onto the existing oligosaccharide side chains of rhGAA also confers spacer length that could minimize the effect of steric hindrance during receptor binding.

Additionally, conjugation of phosphopentamannose-hydrazine onto rhGAA did not affect the enzyme's hydrolytic activity (data not shown). Conjugation efficiency was determined to be high and to have occurred on nearly all the rhGAA molecules, as evidenced by an increase in the binding of the phosphopentamannose-conjugated rhGAA to a CI-MPR column, shown in FIG. 7, where closed circles represent conjugated rhGAA and open circles represent rhGAA. While only approximately 40% of the original rhGAA bound the CI-MPR column, the column retained greater than 90% of the phosphopentamannose-conjugated rhGAA. Therefore, the conjugation process used to modify the oligosaccharides on rhGAA was efficient and did not measurably alter its activity. However, conjugation with phosphopentamannose did not enhance its uptake into L6 myoblasts in vitro when compared to the unmodified enzyme (data not shown). This may be attributed to relatively low-affinity of phosphopentamannose to CI-MPR.

Example 6

Conjugation of Mono- and Bis-Phosphorylated Oligomannose Residues onto rhGAA Improved its Binding to CI-MPR

Soluble CI-MPR was purified from fetal bovine serum using a phosphopentamannose column according to the method of Li et al. (1 *GLYCOBIOLOGY* 511-517 (1991)). The purified CI-MPR (1 mg) was coupled to 1 ml Affigel-15 beads (BioRad) essentially as outlined by the manufacturer. Binding of rhGAA or M6P-conjugated rhGAA to the CI-MPR column was performed as described by Valenzano et al. (270 *J. BIOL. CHEM.* 16441-16448 (1995)). The M6P content of rhGAA and modified rhGAA (neo-rhGAA) was analyzed using the method described by Zhou et al. (306 *ANAL. BIOCHEM.* 163-170 (2002)). Oligosaccharide profiling of the purified M6P-containing oligosaccharides following endoglycosidase Hf digestion of α -galactosidase A was performed according to the method of Townsend and Hardy. (1 *GLYCOBIOLOGY* 139-147 (1991)).

To generate a modified rhGAA (neo-rhGAA) with high affinity for the CI-MPR, M6P-containing oligosaccharides were isolated from recombinant human α -galactosidase A and conjugated onto rhGAA, as described supra. Recombinant α -galactosidase A was used as a source of the oligosaccharides because analysis of its carbohydrate content, as shown in FIG. 8A, indicated that 30 to 40% of the high-mannose oligosaccharides are bis-phosphorylated in α -galactosidase A, which is expected to result in high affinity for the CI-MPR. Phosphorylated high mannose oligosaccharides (both mono- and bis-phosphorylated) were released from α -galactosidase A by endoglycosidase H treatment, purified over a QAE column and analyzed by dionex column chromatography, shown in FIG. 8B.

Conjugation of the purified mono- and bis-phosphorylated oligosaccharides onto rhGAA (neo-rhGAA) resulted in an increase in the fraction of enzyme that bound to the CI-MPR column, as shown in FIG. 9, which shows an increase in binding of neo-rhGAA to the CI-MPR column (represented by closed circles), relative to rhGAA (represented by open circles), and periodate-treated rhGAA (represented by open squares).

As depicted in FIG. 9, approximately 63% of the modified rhGAA (neo-rhGAA) bound to the CI-MPR column compared to approximately 40% for the unmodified enzyme. The periodate-treated non-conjugated rhGAA (open squares in FIG. 9) displayed binding characteristics that were similar to that for untreated rhGAA, (open circles in FIG. 9), suggesting that the increased binding of neo-rhGAA (closed circles in FIG. 9) was not-due to non-specific interactions between the oxidized sialic acids on rhGAA and the CI-MPR column.

A likely reason for a lower than expected fraction of rhGAA containing mono- and bis-M6P (63%, as opposed to $\geq 90\%$ for phosphopentamannose-conjugated rhGAA) to bind the CI-MPR column is that smaller amounts of the phosphorylated oligosaccharides were used in the conjugation reaction.

Example 7

Conjugation of Mono- and Bis-Phosphorylated Oligomannose Residues onto rhGAA Improved its Uptake into Cells In Vitro

L6 myoblast cells (ATCC) were plated onto 12-well culture dishes and allowed to settle for 24 hours. Prior to the addition of enzyme to the cells, cells were washed once with 3 ml DMEM (Invitrogen, Carlsbad, Calif.). Various forms of rhGAAs in 1 ml of uptake media (DMEM containing 1% (v/v) heat inactivated FBS, 25 mM Hepes (pH 6.8), 2.5 mM β -glycerolphosphate and antibiotics) were added to cells and incubated at 37° C. for 18 hours. In some of the wells, 5 mM M6P was added to inhibit CI-MPR mediated uptake. After 18 hours, cells were washed twice with PBS containing 1 mM M6P and then twice more with PBS alone. Cells were lysed in GAA assay buffer (0.2 M sodium acetate, 0.4 M potassium chloride, pH 4.3) containing 0.1% Triton X-100 by scraping the cells followed by sonication. Cell lysates were centrifuged at 14,000 g for 10 min at 4° C. and the GAA activity in the cleared supernatants was assayed using the fluorogenic substrate 4-methylumbelliferyl- α -D-glucopyranoside. (Sigma Chemical Co., St. Louis, Mo.) (J. L. Van Hove et al., 9 *PROC. NATL. SCI. USA* 65-70 (1996)). Protein content in the cell lysates was determined using the microBCA kit (Pierce) with BSA as a standard.

Monosaccharide analysis of the neo-rhGAA confirmed that the modified enzyme contained higher levels of phosphorylated oligomannose residues. The M6P content was increased from about 0.9 mole M6P/mole of unmodified rhGAA, to 2.9 mole M6P/mole of modified rhGAA (neo-rhGAA). Importantly, this increase in M6P-containing oligosaccharides on neo-rhGAA resulted in a significant enhancement in its uptake by L6 myoblasts, as shown in FIG. 10. GAA activity was measured for increasing amounts of rhGAA (open circles in FIG. 10) or neo-rhGAA (closed squares in FIG. 10). Uptake of neo-rhGAA approached saturation at 100 nM compared to approximately 500 nM for the unmodified rhGAA. This is consistent with an increase in the affinity of neo-rhGAA for the CI-MPR, presumably because of the conjugation of additional M6P-containing ligands. Uptake was completely blocked by the addition of excess M6P, confirming that the uptake of the enzyme by the L6 cells was primarily mediated via the CI-MPR (data not shown).

Example 8

Clearance of Glycogen from Pompe Mouse Tissues was Improved with Neo-rhGAA

In order to determine whether the improved uptake of modified rhGAA (neo-rhGAA) in vitro in cells correlates

with a greater reduction in glycogen storage in vivo in mice, Pompe mice were treated either with neo-rhGAA or unmodified rhGAA. (N. Raben et al. 273 J. BIOL. CHEM. 19086-19092 (1998)). Animal experiments were conducted in accordance with the Guide for the Care and Use of Laboratory Animals (U.S. Department of Health and Human Services, NIH Publication No 86-23).

Four to five month-old Pompe mice were used to evaluate the relative ability of various rhGAAs to reduce glycogen storage in the affected tissues. (N. Raben et al. supra). Groups of Pompe mice (7 animals/group) were injected via the tail vein with a vehicle (25 nM sodium phosphate, pH 6.5; 1% mannitol; 0.005% Tween-80) and varying doses of rhGAA or modified rhGAA (neo-rhGAA). Mice were administered three weekly doses and killed two weeks after the last treatment. Various tissues including the heart, diaphragm and skeletal muscles were collected and stored at -80°C . until further analysis. Statistical analysis was performed using one-way ANOVA followed by a Newman-Keuls test. A probability value of $P < 0.05$ was considered statistically significant.

The glycogen content in the various muscles of the Pompe mice was assayed by measuring the difference in the amount of glucose released from a boiled tissue homogenate following digestion in presence or absence of *Aspergillus niger* amyloglucosidase, as described previously. (A. Amalfitano et al., 96 PROC. NATL. ACAD. SCI. USA 8861-8866 (1999)). The glucose levels were assayed using the Amplex Red glucose assay kit (Molecular Probes, Eugene, Oreg.), according to the manufacturer's instructions. Bovine liver glycogen (Sigma Chemical Co.) was used as a standard. In some studies, glycogen content was measured using periodic acid Schiff (PAS) staining followed by computer-assisted histomorphometric analysis (Metamorph) as described previously. (N. Raben et al., 80 MOL. GENET. METAB. 159-169 (2003)). All photography and MetaMorph analyses were performed in a blinded manner.

Approximately 24% and 46% higher enzyme levels were detected in the skeletal muscle and heart tissues, respectively, in animals that were administered neo-rhGAA compared to those treated with the unmodified rhGAA. Treatment with either form of the enzyme (modified neo-rhGAA or unmodified rhGAA) resulted in a dose-dependent reduction in the glycogen levels in all tissues examined, as depicted in FIGS. 11A-11D, which is representative of two independent experiments with 7 animals in each group. However, mice treated with neo-rhGAA uniformly displayed a greater reduction in levels of glycogen in all the muscles analyzed, as depicted in FIGS. 11A-11D.

In the heart, an approximately four to six fold greater reduction in glycogen levels was attained with neo-rhGAA than with rhGAA at both the 10 and 20 mg/kg doses (FIG. 11C). Significantly higher reduction in glycogen levels was also observed in the other muscle tissues of animals that had been treated with the modified enzyme, as summarized in FIGS. 11A, 11B and 11D. An approximately 50% reduction in glycogen level was attained with 20 mg/kg neo-rhGAA in the quadriceps muscle (FIG. 11A) and to a lesser degree in the triceps (FIG. 11B) and diaphragm (FIG. 11D). In nearly all cases, the efficacy attained with only 20 mg/kg of modified rhGAA (neo-rhGAA) was similar to that achieved with 50 mg/kg of unmodified rhGAA, thereby suggesting that a lower dose of the modified rhGAA was sufficient to attain a desirable result. In general, the skeletal muscle tissue was more refractory than the heart and attained only a 50-60% reduction in glycogen levels at the 20 mg/kg dose compared to a nearly a 95% reduction in glycogen levels in the heart. (N.

Raben et al., 80 MOL. GENET. METAB. 159-169 (2003); N. Raben et al., 6 MOL. THER. 601-608 (2002)).

The reduction in glycogen levels observed by biochemical analysis was confirmed by histomorphometric assessment of the quadriceps muscles obtained from the same animals. Tissue samples were stained for lysosomal glycogen followed by analysis of tissues by high resolution light microscopy (HRLM). Lysosomal glycogen appeared as discreet, purple beaded structures scattered throughout each myocyte (data not shown). With enzyme treatment, however, these glycogen-containing structures became smaller and fewer in number. The administration of 20 mg/kg of modified rhGAA (neo-rhGAA) resulted in about a 54% reduction in the tissue area occupied by glycogen, when compared to the vehicle treated negative control samples. This reduction was nearly as effective as the administration of 50 mg/kg of unmodified rhGAA which provided for nearly a 60% reduction, suggesting that neo-rhGAA was 2 to 2.5 times more potent than rhGAA. The results from one such experiment are summarized in FIG. 12, which depicts the percentage of area occupied by glycogen in quadriceps muscle sample in vehicle control (A); 10 mg/kg rhGAA (B); 50 mg/kg rhGAA (C); and 20 mg/kg neo-rhGAA (D).

Example 9

Modifying rhGAA with Synthetic Bis-M6P Glycans Increased its Binding to CI-MPR without Affecting its Enzymatic Activity

A. Derivation of Synthetic Bis-M6P-Oligomannose Hydrazide

In order to determine whether synthetic forms of modified rhGAA would be as or more effective than the neo-rhGAA described above, synthetic bis-M6P oligomannose oligosaccharides were conjugated onto rhGAA.

Synthetic bis-M6P glycan was designed based on the in vivo process of M6P phosphorylation that occurs on naturally occurring high-mannose structure of lysosomal enzymes. (Kornfeld and Mellman, 5 ANNUAL REVIEW OF CELL BIOLOGY 483 (1989)). Synthetic bis-M6P oligomannose glycan was derived from the high mannose structure shown in FIG. 13A and was custom synthesized by BioMira (Edmonton, Alberta, Canada).

The middle antennary arm shown in (b) and one terminal mannose in (c) were removed, resulting in bis-M6P oligomannose, which was subsequently derivatized with a carbonyl reactive compound, butyryl hydrazide. The removal of the middle arm was believed to offer flexibility and improved pharmacokinetics by reducing competition against mannose receptors on macrophages and sinusoidal endothelial cells. This derivatized highly phosphorylated mannose oligosaccharide called bis-M6P-hydrazide, shown in FIG. 13B, was subsequently conjugated onto rhGAA.

B. Chemical Conjugation of Bis-M6P Hydrazide onto rhGAA

Recombinant human GAA (rhGAA) (Genzyme Corp.) was dialyzed twice against 4 liters of 0.1 M sodium acetate (pH 5.6) for 18 hours at 4°C . Approximately 10 mg/ml of dialyzed rhGAA was oxidized with 7.5 mM sodium metaperiodate for 30 minutes on ice. Excess sodium metaperiodate was removed by the addition of 50% glycerol and incubation on ice for 15 minutes. The oxidized rhGAA was then dialyzed against 4 liters of 0.1 M sodium acetate (pH 5.6). Five hundred milligrams of the oxidized rhGAA was conjugated to the bis-M6P-hydrazide by mixing and incubating at 37°C . for 2 hours. After conjugation, neoGAA samples were

dialyzed three times against 4 liters of 25 mM sodium phosphate buffer (pH 6.75) containing 1% mannitol and 0.005% Tween-80 over 24 hours at 4° C. and then sterile filtered. The samples were aliquoted, snap-frozen on dry ice and stored at -80° C. until further analysis.

C. CI-MPR Column Fractionation and In Vitro Cell Uptake

Binding of neo-rhGAA and rhGAA to CI-MPR and in vitro uptake of rhGAA into L6 myoblast cells was evaluated essentially as described above. For uptake of GAAs into macrophages, NR8383 macrophage cells (ATCC, Manassas, Va.) were grown in T150 flasks. Prior to the uptake assay, cells were collected, washed once with Kaighan's media (Invitrogen) without serum and resuspended in uptake media (Kaighan's media+1.5% FBS+25 mM Hepes, pH6.8) at a concentration of $0.6-1 \times 10^6$ cells/ml. One ml of cells were aliquoted into microfuge tubes containing 25 nM of rhGAA or neo-rhGAA and to some of the tubes, either 2 mg/ml of yeast mannan was added to inhibit uptake mediated by mannose receptor, or 5 mM M6P to inhibit uptake mediated by CI-MPR. Uptake was continued for 2 hours at 37° C. and cells were harvested by centrifugation, washed twice with PBS containing 1 mM M6P and 1 mg/ml mannan, and then twice with PBS alone.

All cells were lysed in GAA assay buffer and assayed for GAA activity using 4-methylumbelliferyl- α -D-glucopyranoside as described above.

As depicted in FIG. 14A, direct conjugation of bis-M6P-hydrazide to periodate oxidized rhGAA did not affect its specific enzymatic activity. Furthermore, the neo-rhGAA thus generated had increased binding to the CI-MPR column, as depicted in FIG. 14B. In fact, more than 95% of neo-rhGAA now bound to the CI-MPR column compared to only about 30% of the unmodified rhGAA that bound to the column.

Consistent with the increased CI-MPR column binding, monosaccharide analysis of the neoGAA confirmed that the modified enzyme contained higher levels of phosphorylated oligomannose residues. The M6P content was increased from average of 0.9 mole M6P/mole of unmodified rhGAA to about 15 mole M6P/mole of neo-rhGAA, which translates to about 7 bis-M6P glycans conjugated onto the neo-rhGAA.

Furthermore, consistent with a higher affinity for the CI-MPR, the neo-rhGAA also exhibited an improved uptake by L6 myoblasts. As shown in FIG. 15A, uptake of neo-rhGAA approached saturation at about 25 nM (closed squares) compared to approximately 500 nM for the unmodified rhGAA (closed circles). Uptake was blocked by the addition of excess M6P, confirming that the uptake of the enzyme by the L6 cells was primarily mediated via the CI-MPR. Based on the half maximal value of uptake, the dissociation constant (kd) of neo-rhGAA to CI-MPR was estimated to be around 2.5 nM, a value in agreement with the Kd of the natural bis-M6P oligosaccharides previously reported. (Tong et al., 264 J. BIOL. CHEM 7962-7969 (1989)). In contrast, the Kd of the unmodified rhGAA to CI-MPR was about 100 nM, also close to the experimentally determined Kd for mono-M6P bearing oligosaccharides previously reported. (Distler et al., 266 J. BIOL. CHEM. 21687-21692 (1991)).

Mannose receptors on macrophage cells and sinusoidal endothelial cells are considered to be responsible for the clearance of glycoproteins in vivo by binding to mannose residues. In order to determine whether the addition of bis-M6P glycans on neo-rhGAA affects its uptake by mannose receptors, an in vitro cell uptake assay was performed with macrophages. As depicted in FIG. 15B, uptake of rhGAA was barely detectable after 2 hours even at 25 nM concentration. Furthermore, inclusion of inhibitors for CI-MPR and mannose receptor did not change the GAA activity in these cells.

However, uptake of neo-rhGAA was readily detectable and was inhibited by M6P, but not by mannan, indicating that the increase in uptake into macrophages was mediated by M6P.

Example 10

Modifying rhGAA with Bis-M6P Hydrazide Resulted in a Significant Improvement in Glycogen Clearance in Young Pompe Mice

To determine whether the improved uptake and targeting properties of neo-rhGAA conjugated with synthetic glycan would result in a greater reduction in glycogen storage, young Pompe mice (5 months of age) were treated with either neo-rhGAA or unmodified rhGAA. Animal studies were conducted in accordance with the Guide for the Care and Use of Laboratory Animals (U.S. Department of Health and Human Services, NIH Publication No 86-23). Groups of Pompe mice (5-7 animals/group) were injected via the tail vein with vehicle and varying doses of either rhGAA or neo-rhGAA. Mice were administered four weekly doses and sacrificed one week after the last treatment. Various tissues including the heart, diaphragm and three skeletal muscles were retrieved and stored at -80° C. until further analysis. Statistical analysis was performed using one-way ANOVA followed by a Newman-Keuls test. A probability value of $P < 0.05$ was considered statistically significant.

Glycogen content in the various muscles of the Pompe mice was assayed by measuring the difference in the amount of glucose released from a boiled tissue homogenate following digestion with or without *Aspergillus niger* amyloglucosidase, as described above. Glucose levels from the digested and undigested sample sets were then assayed using the Amplex Red glucose assay kit according to the manufacturer's instructions. Bovine liver glycogen was used as a standard. In some studies, glycogen content was measured using periodic acid Schiff (PAS) staining followed by computer-assisted histomorphometric analysis (MetaMorph) as described above. All photography and MetaMorph analyses were performed in a blinded manner.

Treatment with either form of the enzyme resulted in a dose-dependent reduction in the glycogen levels in all the tissues examined, as depicted in FIG. 16. At equivalent doses, mice treated with neo-rhGAA uniformly displayed a greater extent of glycogen reduction in all the muscles analyzed, as shown in FIG. 16. In the heart and diaphragm, similar glycogen clearance was achieved with an approximately eight-fold reduced dose of neo-rhGAA relative to rhGAA. For example, 2.5 mg/kg and 5 mg/kg of neo-rhGAA achieved nearly the same glycogen reduction as 20 mg/kg and 40 mg/kg of rhGAA respectively. Significantly higher reduction in glycogen levels was also observed in skeletal muscles of animals that had been treated with the modified enzyme. Overall, the dose amount of modified rhGAA that was required to achieve a reduction in glycogen levels similar to that with rhGAA, was about four-fold less than the rhGAA in the quadriceps, triceps and psoas muscles examined.

Consistent with previous reports, the heart responded to GAA treatment better than the skeletal muscles which are generally more refractory to treatment, whether by rhGAA or neo-rhGAA. Four weekly doses of 10 mg/kg of neo-rhGAA completely cleared glycogen in the heart to normal levels, whereas 20 mg/kg of neo-rhGAA was required to clear glycogen in the diaphragm and quadriceps. However, for triceps and psoas, at 20 mg/kg dose, some glycogen remained in the muscles, as depicted in FIG. 16.

In an independent study with higher rhGAA and neo-rhGAA doses, it was observed that four weekly doses of 20 mg/kg of neo-rhGAA attained similar glycogen clearance as in case of 100 mg/kg rhGAA in the skeletal muscles, and 40 mg/kg of neo-rhGAA was required to clear glycogen in tri-

ceps and psoas muscles to near normal level (data not shown). The reduction of glycogen observed by biochemical assay was confirmed by histomorphometric assessment of heart and quadriceps muscle samples obtained from the same study. By high resolution light microscopy, lysosomal glycogen appeared as discreet, purple beaded structures scattered throughout each myocyte. With enzyme treatment, these glycogen-containing structures become smaller and fewer in number. (data not shown). Administration of 20 mg/kg rhGAA resulted in clear reduction in the number of glycogen granules and percent tissue area occupied by glycogen in the heart when compared to vehicle treated samples; however, less discernible glycogen clearance was observed in quadriceps at this dose of rhGAA. In both cases, significant glycogen remained in tissues. In contrast, in both heart and quadriceps of Pompe animals treated with neo-rhGAA at this dose, near complete clearance of glycogen were attained. Occasionally, glycogen granules that appear to be cytoplasmic and resistant to treatment could be seen.

Example 11

Modifying rhGAA with Bis-M6P Hydrazide Resulted in a Significant Improvement in Glycogen Clearance in Old Pompe Mice

The glycogen storage in old Pompe mice is more resistant to GAA treatment. This has been attributed, at least in part, to tissue damage in old mice that generally results in less efficient uptake of GAA by target muscle cells. To determine if

neo-rhGAA would have similar beneficial effects in old Pompe animals, as in young mice, thirteen month old Pompe mice were used for evaluation. About 10 animals/group were treated with 40 mg/kg of either rhGAA or neo-rhGAA and the same tissues were harvested and assayed for glycogen content as for the younger mice.

As shown in FIG. 17, significantly less glycogen were cleared by 40 mg/kg of rhGAA in all the tissues examined, as compared to the young mice. From biochemical analysis of glycogen content, it was estimated that only about 80% of the glycogen were cleared in the heart, and only 10-40% of the glycogen was cleared from other tissues of old Pompe mice treated with rhGAA. However, despite being more refractory to rhGAA treatment, glycogen storages were completely cleared from the heart and diaphragm, >90% in quadriceps and >80% in triceps and psoas when these old animals were treated with 40 mg/kg of neo-rhGAA.

The increased glycogen clearance by neo-rhGAA over rhGAA in old Pompe mice were also confirmed by PAS staining and high resolution light microscopic analysis of representative tissues of the heart and quadriceps (data not shown). Again, as in case of young mice, glycogen granules appeared to be cytoplasmic and resistant to clearance were occasionally seen in few muscle cells.

All primary references cited herein are hereby incorporated by reference in their entirety, together with the references contained therein.

The explanations and illustrations presented herein are intended to acquaint others skilled in the art with the invention, its principles, and its practical application. Those skilled in the art may adapt and apply the invention in its numerous forms, as may be best suited to the requirements of a particular use. Accordingly, the specific embodiments of the present invention as set forth are not intended as being exhaustive or limiting of the invention.

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What is claimed is:

1. A method of treating Fabry disease comprising administering to a subject in need thereof a modified α -galactosidase A prepared by:

(a) derivatizing an oligosaccharide comprising a phosphorylated mannose with a compound containing a carbonyl-reactive group;

(b) oxidizing an α -galactosidase A having at least one oligosaccharide to generate at least one carbonyl group on the at least one oligosaccharide of the α -galactosidase A; and

(c) reacting the derivatized oligosaccharide with the oxidized α -galactosidase A, thereby coupling the oligosaccharide to the α -galactosidase A.

2. The method of claim 1, wherein the oligosaccharide is a biantennary mannopyranosyl oligosaccharide.

3. The method according to claim 2, wherein the biantennary mannopyranosyl oligosaccharide comprises bis-M6P.

4. The method of claim 1, wherein the α -galactosidase A is oxidized by contact with periodate or galactose oxidase.

5. The method of claim 1, wherein the carbonyl-reactive group comprises a hydrazine, hydrazide, aminoxy, or semicarbazide.

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